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## David Taylor Research Center

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**Ship Materials Engineering Department**

## Research and Development Report

# The Effect of Weld Metal Strength Mismatch on the Deformation and Fracture Behavior of Steel Butt Weldments

by

**Mark T. Kirk**

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# The Effect of Weld Metal Strength Mismatch on the Fatigue Crack Growth Rate of Steel Butt Weldments

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Mark T. Kirk

## Table of Contents

List of Tables	iv
List of Figures	v
Abstract	vii
Administrative Information	vii
Introduction	1
Weldment Deformation	3
1951 - Hartbower and Pellini - Explosion Bulge Tests	3
1970 to 1978 - Satoh, Toyoda, and Co-Workers - Tensile and Wide Plate Tests	5
1983 - Patchett and Bellow - Tensile Tests	6
Summary and Closure	7
Weldment Fracture	7
Weld Strength Matching Effects on Applied $J_I$ and $\delta$	8
Single Edge Notch Specimens	9
Wide Plate Specimens	12
Weld Strength Matching Effects on Fracture Toughness	16
Overall Summary	17
References	46



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Unannounced	J
Justification	J
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Distribution/	
Availability Codes	
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## **List of Tables**

- Table 1:** Effect of Weld Joint Geometry on Strain Localization in Elliptical Explosion Bulge Tests of Overmatched Welds.
- Table 2:** Finite Element Results of Bleackley, et al. Illustrating the Effects of Weld Joint Geometry on Applied  $J_I$ .
- Table 3:** Wide Plate Conditions Investigated by Dong and Gordon.
- Table 4:** Wide Plate Conditions Investigated by Zhang, et al.

## List of Figures

- Figure 1: Common microstructural and toughness variations in a single pass steel weldment, condensed from Kerr [1976].
- Figure 2: Expanded view of experimental set-up for explosion bulge tests [Hartbower and Pellini, 1951(a) and 1951(b)].
- Figure 3: Strain distribution transverse to double-V groove weldments in explosion bulge test panels [Hartbower and Pellini, 1951(a)].
- Figure 4: Influence of weld layer thickness (gap between plates joined) on the ultimate tensile strength of the weldment for round bar specimens [Sato and Toyoda, 1970(a)].
- Figure 5: Influence of weld layer thickness (gap between plates joined) / bar diameter ( $X$  value) on the failure strain ( $F$ ) and strain at maximum load ( $M$ ) for 50% undermatched round bar specimens [Sato and Toyoda, 1970(a)].
- Figure 6: Effect of testpiece aspect ratio on the weldment ultimate tensile strength [Sato and Toyoda, 1970(b)].
- Figure 7: Effect of weld groove geometry and panel width on the ultimate tensile strength and ultimate tensile elongation of 70mm thick HT80 weldments [Sato and Toyoda, 1975].
- Figure 8: Effect of weld layer thickness on weldment yield and ultimate tensile strength for rectangular cross section tension specimens (width to thickness ratio of 1.5:1) cut from stress relieved ASTM A516 Grade 70 weldments [Patchett and Bellow, 1983].
- Figure 9: Schematic diagram of testpieces for fracture mechanics tests of weldments.
- Figure 10: Schematic diagram of Engineering- $J$  design curve format [Turner, 1983].
- Figure 11: Effect of strength matching ratio on the variation of  $J$  with applied strain for 0.1  $a/W$  SE(B) specimens [Cray, et al., 1989].
- Figure 12: Plastic strain distribution in 30% undermatched double-V butt weldments loaded in remote tension (top) and in remote bending (bottom). Crack depth was 10% of panel thickness. [Cray, et al., 1989]
- Figure 13: Effect of crack depth, loading mode, and strength matching ratio on the Engineering- $J$  design curve slope of single edge notch specimens once yielding has occurred. (a) SE(B) specimens. (b) SE(T) specimens. [Cray, et al., 1989]
- Figure 14: Effect of crack depth on applied  $J_I$  for SE(B) specimens with 25% overmatched butt welds [Dong and Gordon, 1990].
- Figure 15: Schematic diagram of instrumentation plan for  $J$ -contour measurements on surface cracked wide plate testpieces [Read and Petrovski, 1990].

- Figure 16: Effect of strength matching ratio on the applied  $J_I$  value developed by a wide plate tension specimen (75 mm x 15 mm cross section) having a surface crack 10 mm long x 3 mm deep on the centerline of a double-V butt weld. Weld and crack were both oriented perpendicular to the loading direction [Read and Petrovski, 1990].
- Figure 17: Effect of strength matching ratio on the applied  $J_I$  value developed by a wide plate tension specimen (75 mm x 15 mm cross section) having a surface crack 25 mm long x 6 mm deep on the centerline of a double-V butt weld. Weld and crack were both oriented perpendicular to the loading direction [Read and Petrovski, 1990].
- Figure 18: Effect of weld layer thickness ( $h$ ) to crack length ( $2a$ ) ratio on applied  $J_I$  developed in wide plates made from square-groove 37% overmatched butt weldments containing a central through crack cutting 20% of the panel width. Both crack and weld are oriented perpendicular to loading direction [Weidian, et al., 1989].
- Figure 19: Effect of strength matching ratio on applied  $J_I$  for welded wide plates having through cracks of 5% of the panel width [Dong and Gordon, 1990].
- Figure 20: Effect of strength matching ratio on applied  $J_I$  for welded wide plates having through cracks of 20% of the panel width [Dong and Gordon, 1990].
- Figure 21: Variation of effective yield stress with the ratio of weld layer thickness to crack length for wide plates made from square-groove butt weldments containing a central through crack cutting 40% of the panel width. Both crack and weld are oriented perpendicular to loading direction. (a) 20% Undermatched. (b) 25% Overmatched. [Zhang, et al., 1990].
- Figure 22: Variation of effective strain hardening exponent with the ratio of weld layer thickness and hardening matching ratio to crack length for wide plates made from square-groove butt weldments containing a central through crack cutting 40% of the panel width. Both crack and weld are oriented perpendicular to loading direction. (a) 20% Undermatched. (b) 25% Overmatched. [Zhang, et al., 1990].
- Figure 23: Consolidated plot from the results of Zhang, et al. [1990] showing the variation of effective strain hardening exponent with the ratio of weld layer thickness for common ferritic-pearlitic and martensitic steels. Undermatched welds (on strength) are overmatched for strain hardening, while overmatched welds (on strength) are undermatched for strain hardening.
- Figure 24: Effect of strength matching (23% undermatched vs. 1% over) on critical fracture toughness ( $\delta_c$ ) values determined by testing deeply notched SE(B) specimens cut from 50 mm thick HT80 steel weldments [Sato, et al., 1979].
- Figure 25: Effect of strength matching ratio on critical fracture toughness (minimum of three  $\delta_c$  values at  $+10^\circ\text{C}$ ) for various self shielded flux core weldments between BS 4360 grade 50D plate [Cunha and Pope].

## **Abstract**

Considerable Naval and industrial experience dating from the explosion bulge studies of Pellini and Hartbower in the early 1950s has indicated the engineering utility of using weld metal having strength greater than the plates being joined (overmatching). Overmatching shields the weld region, which typically has lower toughness than the plate and is often the site of defects, from the high strains that develop during an overload. This practical advantage, coupled with the ease of achieving overmatch in lower strength steel alloys (80 ksi yield strength or less) has led to codification of overmatching as a requirement in most structural design codes and fabrication specifications. However, overmatching has certain economic and technical disadvantages which undermatched (weld metal strength less than plate strength) systems might alleviate. This report reviews investigations concerning the deformation and fracture characteristics of simple mechanical test specimens containing butt welds, focusing on how the relative strength of the weld deposit and the plate influences these characteristics. All analytical and experimental evidence available indicates that plastic strain concentrates into the zone of the lowest material strength in a transversely loaded weldment. Thus, plastic strains in undermatched weldments concentrate in the weld deposit while in overmatched weldments they concentrate in the plate. Data for both remote bending and for remote tension loading indicates that the driving force to fracture ( $J_I$ ) for a crack in an undermatched weldment generally increases at a much faster rate with increasing plastic strain than for a crack in an undermatched weldment. This effect of weld mismatch is most pronounced for cracks that are either shallow with respect to the testpiece thickness (less than approximately 30% through wall) or small with respect to the gross load bearing cross section (less than between 4% and 21% area reduction). Implications of these trends to the relation between applied load and  $J_I$  for both bend and tension specimens containing cracks in the weld are discussed.

## **Administrative Information**

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## Introduction

Steel civil and marine engineering structures are often fusion welded to achieve the greatest construction economy. The fracture integrity of such structures depends on both the loads carried by and the resistance to fracture (fracture toughness) of the various structural components. Neither the weld deposit nor the heat affected zone (HAZ) at the weld metal – base plate interface has fracture properties that are as well controlled or as high (in general) as that of the plates or shapes being joined. The following paragraphs address these points in greater detail.

The need to make weldments in the field, rather than in the more controlled environment of a steel mill complicates control of weldment toughness. Further, variables that significantly influence weldment toughness, such as peak temperature and cooling rate, cannot be economically monitored during welding. Instead, these variables are controlled indirectly by specifying allowable ranges on variables the welder can control (e.g. welding current, welding voltage, travel speed, arc length, etc.). However, construction costs increase quickly if these allowable ranges are too small. Finally, weldments are influenced to a much greater degree than plate and shape production by the workmanship of an individual tradesman. Designers sometimes make maintaining high quality workmanship difficult by placing welds in restricted access locations. However, even elimination of such details cannot insure good workmanship in all instances because factors such as weather, worker morale, and workload influence workmanship. These factors are beyond the control of the design engineer.

The fracture toughness of steel weldments is characteristically heterogeneous. For a fixed chemistry, the local thermal history controls the room temperature fracture toughness at each location in the weldment [Kerr, 1976]. Figure 1 presents a schematic diagram of a single pass weldment in a mild steel plate and shows the relation between the peak temperature, the room temperature microstructure, and the fracture toughness properties of each region. The specific relation of plate toughness to that of the various HAZs and of the weld metal depends on the type of steel welded. In some cases certain regions of the HAZ may have improved fracture toughness relative to the plates joined. For example, the grain refined HAZ will have better toughness than most mild steels because a reduction of grain size generally increases fracture toughness. In contrast, the grain refined HAZ in a microalloyed steel

may have inferior toughness to the plate because this type of steel plate has a fine grain structure before welding. What can be said in general is that certain regions of the weldment will always have inferior toughness relative to the plate. Specifically, these include the coarse grain HAZ (owing to the large grain size) and the weld metal (owing to the as-cast structure). In multi-pass welds, the various regions shown in Figure 1 interact due to re-thermal cycling by subsequent weld passes. The toughness of some regions are improved by this thermal cycling while some are degraded. In the HAZ, a coarse grain structure reheated into the intercritical region experiences incomplete transformation to austenite and, upon cooling, has a coarse grained, dual phase microstructure of extremely low toughness [Machida, et al., 1990]. The weld metal region of a multi-pass weldment retains some of the as-cast structure, but also includes microstructures characteristic of all of the different heat affected zones due to thermal cycling effects. Thus, the solidified weld metal may contain regions of higher toughness than the plate, but will certainly contain lower toughness regions as well.

In addition to causing quality control difficulties and introducing low toughness regions, welding can also produce defects whose presence must be considered to insure structural integrity against fracture. Such defects are either planar / crack-like (e.g. cold cracking, lack of fusion, hot tearing, lack of penetration, or undercut) or volumetric (e.g. porosity, entrapped slag) and may be either undetectable or not economically detectable using non-destructive techniques. Some defects are serious on their own, while others serve as initiation sites for fatigue cracking during service. Taken together, these various factors provide the designer with considerable incentive to prevent development of high strains in welded regions. For this reason, many codes require use of weld metals whose strength exceeds that of the plates joined [ASME, 1980; AWS, 1980; USDOT, 1979]; a practice referred to as *overmatching*. Overmatched welds force plastic deformation into the lower strength plate where better fracture resistance and fewer defects are expected, thus shielding the weldment from large strains.

Unfortunately, overmatching weld metal strength has certain economic and technical disadvantages which undermatched (weld metal strength less than plate strength) systems might alleviate. For example, welding of high strength steel usually requires preheat to avoid hydrogen cracking. Satoh and co-workers [1978] demonstrated that preheat requirements

could be cut in half by welding HT-80 steel (80 kg/mm<sup>2</sup>, or 113 ksi, nominal tensile strength) with an undermatched electrode (AWS E9016G, 90 ksi nominal tensile strength) rather than with a matched electrode (AWS E11016G, 110 ksi nominal tensile strength). Not only did this change realize a significant energy savings, but it also increased productivity because the lower preheat temperature allowed extension of the welder's duty cycle in this application (underground penstocks). Howden, et al. [1983] pointed out that, for welding HY steels (80 to 130 ksi nominal yield strength), the use of undermatched welds also increases weld metal deposition rate relative to overmatched practice. Such changes would reduce the need to hold electrodes at an elevated temperature prior to use, reduce the lack of fusion / lack of penetration defect rate (higher heat inputs tend to have better penetration characteristics), reduce restraint stresses, and increase weld metal toughness. This information suggests that overmatched welds, while quite effective for low strength steel construction, may not be as advantageous when fabricating structures from higher strength grades. However, undermatched welds cannot be immediately adopted for use due to the much greater strains that would have to be borne by the weld metal. This report will review investigations concerning the deformation and fracture characteristics of simple mechanical test specimens containing butt welds, focusing on how the relative strength of the weld deposit and the plate influences these characteristics.

## **Weldment Deformation**

Several experimental studies concerning the deformation behavior of welded testpieces were conducted between 1951 and 1983. Earlier works regarding welded structures [Parker, 1957] focused on design details, welding practice, and quality control and are therefore not germane to understanding the influence of weld metal strength on weldment deformation and fracture. The different investigations from 1951 through 1983 are discussed chronologically.

### **1951 – Hartbower and Pellini – Explosion Bulge Tests**

Hartbower and Pellini [1951(a), 1951(b)] discussed an “explosion bulge” test used to study the deformation and fracture behavior of weldments for high-rate, multi-axial loading conditions. Figure 2 illustrates the experimental set-up used; dies having either circular or elliptical cutouts allowed different biaxiality ratios to be investigated. The test plates measured 22-inches wide by 20-inches long with a butt weld in the center of the plate parallel

to the 20-inch dimension. Test plate thicknesses ranged from 0.65 to 1-inch; both double-V and square groove joints were used. Use of several grades of steel plate and welding consumables allowed investigation of strength matching conditions ranging from 17% undermatched to 82% overmatched<sup>1</sup>. Plate thickness reduction was used to measure the set strain distribution in and around the weld developed during explosive loading. Figure 3 presents some of these results from a test series of circular bulges illustrating the effect of changing weld metal while holding base metal constant, and vice versa. Further, it appears that undermatching elevates the strain local to the weld above the globally applied level while overmatching has the opposite effect. Together, these results indicate that the strength of the weld metal relative to the plate controls whether the weld will shed or concentrate strain, not the absolute strength of either constituent. Results of a separate study on elliptical bulges indicate that the geometry of the weld joint influences the effectiveness of overmatching in shielding the weld from global strains. These data, summarized in Table 1, show that an increase in the overmatching ratio of 31% did not offset the effect of the Double-V groove on increasing the proportion of globally applied strain that reached the weld centerline.

Beyond their studies of weldment deformation characteristics, Hartbower and Pellini also commented on fracture patterns that developed in the explosion bulge tests. While strength matching effects on fracture are discussed in a subsequent section, this is mentioned here to help explain the historical bias in favor of overmatching. In their study, Hartbower and Pellini ranked weldment fracture performance by the amount the bulge plate could thin prior to fracture. Invariably, the thinning capacity of the overmatched bulges did not drop off suddenly until much lower temperatures than it did for undermatched bulges. This indicated that, at any fixed temperature, the overmatched weldments absorbed more energy, and thus provided a more damage tolerant construction, than did the undermatched weldments. Further, fractures of the undermatched weldments initiated in and propagated almost entirely in the weld. Conversely, cracks initiated in the weld for only half of the overmatched weldments, and all of these fractures propagated immediately into the plate. The different fracture initiation locations were explained based on the strain concentration or shedding effects illustrated in Figure 3. Cracks always propagated perpendicular to the principal strain direction

1. These matching ratios represent a ratio of the difference between the weld metal and plate stress developed at 0.05 strain divided by the plate stress at 0.05 strain as measured in a uniaxial tensile test.

(transverse to the weld for undermatched specimens vs. along the weld for overmatched specimens). These data demonstrated that overmatching prevented many fractures from initiating in the weld, an extremely beneficial feature because of the many natural notches welds can contain (e.g. lack of penetration, lack of fusion, undercut, etc.). Further, even though this "shielding" was only 50% effective, fractures that initiated in the weld ran directly into the base metal and arrested. Thus, these data demonstrated that the fracture properties of the plate would govern the fracture resistance of a structure fabricated from overmatched welds. The (relative) ease of controlling plate toughness during production makes this very desirable.

### **1970 to 1978 – Satoh, Toyoda, and Co-Workers – Tensile and Wide Plate Tests**

Satoh, Toyoda, and their co-workers published a series of papers concerning the deformation behavior of round bar and flat plate tension coupons having a zone of low strength material perpendicular to the loading axis<sup>2</sup>. These investigators sought to reduce the 150°C preheat needed to produce overmatched welds in HT80 steel (a 80 kg/mm<sup>2</sup> tensile strength, quenched and tempered plate) without developing hydrogen assisted root cracks [Satoh, et al., 1978]. Use of an undermatched welding consumable was expected to significantly reduce the needed preheat. Therefore, Satoh and Toyoda investigated the strength and ductility achievable with undermatched weldments.

Satoh and Toyoda [1970(a)] idealized undermatched weldments as a parallel sided layer of low yield strength material imbedded between two higher yield strength materials. They used both flash-butt and narrow gap welds to match this idealization as closely as possible. These experiments addressed the effects of strength matching ratio, joint layer thickness, and testpiece size on ultimate strength and ductility. Figure 4 shows the results of a series of round bar specimens that undermatched plate yield strength by 28% to 66%. These tests showed that weldment ultimate strength approaches that of the plate as joint thickness decreases, indicating that joint strength depends on both joint geometry and flow properties. In these experiments, joint strength increased due to constriction of plastic flow in the weld layer by the nearby higher strength plate material. Thus, this strengthening occurred by the same mecha-

2. The approach used and conclusions arrived at by these researchers follows the work of two Soviet researchers, Shron and Bakshi [1962(a), 1962(b)], very closely. Comparing the work described above to the 1962 studies, it is apparent that Satoh and Toyoda modelled their initial experiments and theories after the previous Soviet work. However, because Satoh and Toyoda carried the research farther, attention is restricted to their work in this review.

nism as in notched tensile tests where the notch produces a tri-axial stress state. However, while tri-axiality elevates flow properties, it also reduces ductility. Therefore, these investigators also noted a reduction in both the ultimate strain to failure and the strain at maximum load with reduced joint width. Figure 5 presents these data.

In a follow-on study, Satoh and Toyoda [1970(b)] investigated the effect of specimen geometry on their previous findings. Figure 6 shows that plate type specimens had higher ultimate strengths than round bar specimens. Constraint of plastic flow also explains this result. In the round bar, the higher strength plate restricts axial plastic flow of the lower strength weld metal, but deformation can occur in both perpendicular directions. However, the largeness of width relative to thickness in the plate specimen restricts plastic flow in the width direction also. As with the round bar specimens, the ultimate ductility of the plates reduced with reducing weld layer thickness. Thus, the flat plate and round bar specimens produced identical trends.

In their final paper, Satoh and Toyoda [1975] studied the double-V and double-U groove joints commonly used in construction to see if the trends determined from the idealized models applied to production weldments. Figure 7 details the results of these experiments. These tests demonstrated that, for this particular set of geometric conditions, a weld deposit having an ultimate strength 10% below the plate strength could achieve the same ultimate strength properties as an overmatched weldment. Additionally, these data show that undermatching more strongly affects ultimate ductility than ultimate strength. For example, a 34% undermatched weldment retained 94% of the ultimate strength of an overmatched weldment but only 29% of its ultimate ductility. Thus, ductility requirements will most likely limit the acceptability of undermatched welds for service more than strength requirements.

### **1983 - Patchett and Bellow - Tensile Tests**

Patchett and Bellow [1983] conducted a series of tensile tests on undermatched narrow-gap submerged arc weldments (SAW) of an ASTM A516 Grade 70 pressure vessel steel ( $\sigma_{ys} = 299 \text{ MPa}$ ,  $\sigma_{uts} = 496 \text{ MPa}$  transverse to the rolling direction). The performance of undermatched weldments concerned these investigators because post-weld heat treatments often reduce the ultimate strength of this alloy below the requirements of the American Society

of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code [1980]. Their results are similar to those of Satoh and Toyoda, and are mentioned only because they reported the effect of weld layer thickness on yield strength as well as on ultimate strength. As shown in Figure 8, these data indicate that reduced layer thickness elevates only the ultimate strength of a weldment, not the yield strength. This suggests that reducing the joint thickness cannot postpone the beginning of a fracture process that depends on plastic flow.

### **Summary and Closure**

The major findings from the investigations discussed in this section regarding the effects of weld metal strength on the deformation behavior of weldments are as follows:

- Relative to the globally applied strain measured far away from a weldment, the strains local to the weld joint are lower in overmatched welds and higher in undermatched welds.
- Weld joint geometry influences the strains which accumulate there.
- As weld layer thickness decreases, undermatched welds can sustain higher loads but less deformation prior to failure.
- The weld layer thickness does not effect the stress at which the weld metal begins to yield in undermatched welds.

Taken together, these findings indicate that, at a given global strain level, undermatched weld deposits are more highly strained than overmatched weld deposits. These results seem to indicate the superiority of overmatched welds for resisting fracture. However, as indicated by the motivations of these investigators, other considerations, such as the need to prevent hydrogen cracks from developing, the need to eliminate preheat, or the need to allow stress relief may increase the attractiveness of undermatched weldments. Further the suitability of either overmatched or undermatched weldments requires consideration of both the driving force to fracture and fracture resistance because weldments can contain crack-like welding defects, or will most likely develop fatigue cracks during service. These considerations are discussed in the following section.

### **Weldment Fracture**

The resistance of a material to fracture from a pre-existing defect (fracture toughness) and the driving force to fracture caused by structural loads are both quantified by a crack tip characterizing parameter. The stress intensity factor ( $K_I$ ) due to Irwin [1962] is used when

linear elastic conditions prevail. However, if the crack tip plastic zone is not vanishingly small compared to other dimensions (e.g. thickness, crack depth), then use of  $K_I$  is not appropriate. In this regime, the non-linear fracture mechanics (NLFM) crack tip characterizing parameters of crack tip opening displacement ( $\delta$ ) due to Wells [1961; 1963], or the J-integral ( $J_I$ ) introduced by Rice [1967] are both appropriate. For linear elastic loading conditions, all three parameters are related [Rice, 1968], while for post yield loading  $\delta$  and  $J_I$  are related by material flow properties and a geometry factor [Shih, 1983; Wellman, et al., 1984]. These parameters all measure the intensity of the crack tip deformation fields [Rice, 1968] and, within certain limitations, are geometry independent [Shih, 1985; Dodds, et al., 1990]. Thus, NLFM provides a framework for using the value of the crack tip characterizing parameter at crack initiation in a simple laboratory specimen to predict the maximum safe load of a flawed structure.

Experimental procedures for estimating critical values of  $K_I$ ,  $\delta$ , and  $J_I$  using laboratory specimens [ASTM E399, ASTM E1290, ASTM E813] are well established for homogeneous plate materials. Additionally, guidelines exist for performing structural fracture safety assessments using these values [PD 6493, 1980; Harrison, et al., 1980; Kumar, V., 1981; Ibid; 1984]. Unfortunately, similar experimental procedures and guidelines are not established for test specimens and structures containing weldments<sup>3</sup>. The following section summarizes research concerning strength mismatch effects on applied  $J_I$  and  $\delta$  values. Subsequently, a section regarding studies of strength mismatch effects on critical fracture toughness is presented.

### **Weld Strength Matching Effects on Applied $J_I$ and $\delta$**

Various investigators have conducted finite element analyses of single edge notched specimens loaded in tension (SE(T)), loaded in bending (SE(B)), and of tension loaded wide plates. These testpieces are illustrated in Figure 9. Standard experimental procedures employ the SE(B) and SE(T) testpieces to estimate the fracture toughness of metallic materials. In contrast, the wide plate usually serves as a structural scale proof test because the loading

3. It should be noted that the crack tip opening displacement design curve [PD 6493, 1980] and Central Electricity Generating Board [Harrison, et al., 1980] fracture safety assessment procedures do attempt to account for the presence of welds by including design factors for residual stress and guidance on what constitutive properties (plate vs. weld metal) should be used in the analysis. However, these are empirical factors; they do not have a theoretically justified basis.



mode (remote tension) and size of the crack relative to the cross sectional area (very small) more closely model a structure than can a SE(B) or SE(T) specimen.

The analyses reviewed in this section all model the testpiece as a bi-material made up of weld and plate material. The weld and the plate have the same elastic modulus but different post yield flow properties in these models. However, fusion weldments have a heat affected zone of rapidly varying constitutive properties distinct from both the plate and the weld metal. Therefore, the assumed model does not exactly match the problem. However, for intermediate to thick section (say 3/4-inch to 2-inches) multi-pass welds, the HAZ is thin compared to the size of the weld deposit and the plate thickness. Additionally, compared to the size of the zone over which the fracture process occurs (3 $\delta$ ) [Hutchinson, 1983], the HAZ is very far away from the crack tip located on the weld deposit centerline. Thus, except for narrow welds or thin plates, the bi-material assumption should not significantly affect the values of  $J_I$  or  $\delta$  estimated by the finite element analyses.

In the following two sections, work concerning test specimens (SE(B) and SE(T)) and wide plates are discussed separately. In each section, the initial discussion concerns results which lend insight regarding the effect of mismatched welds on applied  $J_I$ . Subsequent discussions focus on the work of researchers who have proposed methods to model or account for these dependencies in a simple J-estimation scheme.

### *Single Edge Notch Specimens*

Tests of single edge notch specimens provide estimates of the fracture toughness of welded materials. Bend tests require lower loads and less elaborate fixturing than tension tests and are therefore more common. Values of applied load, load line displacement ( $\Delta_{LL}$ ), and the increasing separation of the notch surfaces at the specimen edge (crack opening displacement, or COD) are monitored during an experiment as loading progresses to the time of crack initiation by either cleavage (brittle fracture) or microvoid coalescence (ductile fracture). Figure 9 indicates the various measured quantities. These measurements are used to estimate the critical fracture toughness values  $J_{Ic}$  and / or  $\delta_c$  using equations appropriate for un-welded specimens presented in the testing standards [ASTM E1290, ASTM E813]. It is therefore of interest to determine if ignoring the presence of the weld produces significant errors in the  $J_{Ic}$  and  $\delta_c$  estimates, and if so, under what conditions.

Bleackley, Jones, and Luxmoore [1986] investigated the effect of weld joint geometry for 15% undermatched 0.1  $a/W$  (ratio of crack depth,  $a$ , to testpiece width,  $W$ ) SE(T) specimens. These investigators presented their results by plotting the applied  $J_I$  versus load point displacement; the same format as the Engineering- $J$  design curve originally proposed by Turner [1983]. Figure 10 shows the shape of this curve. The initial parabolic variation represents linear elastic response and is therefore not influenced by weld metal matching or joint geometry. Conversely, the slope of the curve for gross section yielding (GSY, the linear portion) may depend strongly on weld metal matching and joint geometry because both factors influence the development of yielding in the specimen. Thus, the value GSY slope indexes the effect of different matching / weld joint geometry conditions on the applied  $J_I$  or  $\delta^4$ , with higher values indicating a more severe fracture condition. Table 2 presents the results due to Bleackley, et al. These data indicate that weld joint geometry can significantly influence the relation between experimentally measurable values (e.g.  $\Delta_{LL}$ ) and the crack tip driving force  $J_I$ . In particular, the applied  $J_I$  for the single-V and square groove welds agreed reasonably well to that estimated for a monolithic specimen made entirely of weld metal. Conversely, the double-V groove weld had much less applied  $J_I$  than predicted by this simple model. The reduction of applied  $J_I$  for the double-V groove relative to the other joint geometries occurred because the width of the joint caused high strains to concentrate inside the weld along the weld metal - plate interface, but these strains did not spread to engulf the crack tip. A later analysis of this same situation by Cray, Luxmore, and Sumpter [1989] explains this in greater detail. This paper is reviewed in the following paragraph.

Cray, Luxmoore, and Sumpter [1989] and Lee and Luxmoore [1990] investigated the effect of matching ratio and crack depth to specimen width ratio on SE(B) and SE(T) specimens made from double-V groove welds. They used the same groove geometry and constitutive properties as did Bleackley, et al. Figure 11 presents their results in Engineering- $J$  design curve format for SE(B) specimens at 0.1  $a/W$ . In virtually every case; under or overmatched, tension or bending; no correspondence exists between the homogeneous and the welded specimens indicating that application of equations in the testing standards will produce erroneous  $J_I$  estimates. The trends are as expected based on work concerning effects of weld metal

4. As indicated on Figure 10, the abscissa of this plot can also be expressed in terms of load, strain, or displacement. The GSY slope will have the same properties indicated above so long as the axes are nondimensionalized appropriately.

matching on the deformation behavior of un-cracked welded joints reviewed earlier. The strain concentration by the undermatched welds increases the applied  $J_I$  relative to plain plate while strain shedding by the overmatched welds reduces the applied  $J_I$ . Conversely, the SE(T) results of Cray, et al. indicate that both under and overmatching reduce the applied  $J_I$  relative to plain plate in general yielding, with undermatching causing the greatest reduction. Examining the different plastic strain distributions developed in tension and in bending (Figure 12) helps explain this unexpected behavior. These plots show that undermatching concentrated plastic deformation into the weld in both tension and bending, but in tension the width of the joint allowed the high strains to focus into slip bands along the weld / plate interface. This deformation pattern kept strains around the crack tip low and, consequently, reduced the applied  $J_I$ .

Cray, et al. also performed finite element analyses for four different  $a/W$  ratios ranging from 0.05 to 0.20. Figure 13 shows the effect of loading mode, matching ratio, and  $a/W$  on the GSY design curve slope. In bending, these data show that overmatching considerably reduces the toughness needed for shallow cracks to resist fracture relative to an undermatched condition. However, increasing the crack depth mitigates this advantage. The trends shown by the tension loaded results are influenced by the deformation concentration along the weld / plate interface. It is not possible to draw any general conclusions from the tension data short of noting that consideration of the presence of the mismatched weld is essential to obtain a reasonable estimate of the applied  $J_I$ .

Dong and Gordon [1990] have also investigated  $J_I$  relations for welded bend specimens. Their work focused on determining how well  $J_I$  values calculated for monolithic bend specimens made entirely of weld metal or base metal compare to the applied  $J_I$  calculated for an overmatched square groove welded SE(B) specimen. Figure 14 presents these results. The results for 0.1  $a/W$  indicate that neither simple homogeneous model gives sufficient accuracy. This finding agrees qualitatively with that of Cray, et al. for double-V grooves. Conversely, the homogeneous model for a deep crack ( $a/W = 0.5$ ) achieved good accuracy by using the constitutive properties of the weld metal. This may occur because the deep crack confines yielding to the net ligament and thereby to the weld metal. If this explanation is correct, it suggests that accurate estimates of applied  $J_I$  for a deeply cracked undermatched weld are

also possible using this procedure. For the undermatched weld, both the loading mode and the undermatching focus deformation into the weld. However, for welds that are very narrow in the remaining ligament of the SE(B) specimen (e.g. a narrow groove weld or a double-V with a small bevel angle) the width of the yielded zone in the ligament of the SE(B) may exceed the width of the weld and the homogeneous approximation will most likely break down.

#### Single Edge Notch Specimens, Summary

The major findings of the investigations summarized above regarding the effect of a weld on the applied  $J_I$  developed in SE(B) or SE(T) specimen are as follows:

- Fixing the matching ratio, crack depth, and remote loading mode, weld groove detail has some effect on the rate at which applied  $J_I$  increases with increasing remote load.
- In bending, undermatching increases the rate at which applied  $J_I$  increases with increasing remote load relative to an unwelded specimen. Overmatching has the opposite effect. This difference between over and undermatched welds reduces as crack depth increases.
- The effects of weld metal matching on SE(T) specimens is not well established because the only analysis of this specimen type performed to date was for a weld joint that focused deformation into the weld but at the weld metal / plate interface rather than at the crack.
- The applied  $J_I$  calculated using established J estimation formulas for a monolithic SE(B) made entirely of weld metal provides a reasonable approximation of the applied  $J_I$  for a deeply cracked overmatched weldment. Provided that this occurs because the bend geometry confines post-yield stresses to the weld metal in the unbroken ligament, then this result should apply in general to any weld tested as a deeply cracked SE(B) if the weld has sufficient width to contain all of the plasticity.

Taken together, this information indicates that experimental investigations concerning weld strength matching effects using deeply notched SE(B) specimens will probably give reasonably accurate results. Conversely, experimental trends and conclusions based on shallow crack fracture tests are questionable if the applied  $J_I$  is estimated based on homogeneous J estimation formulas.

#### *Wide Plate Specimens*

Investigators employing the wide plate specimen commonly use it as a structural scale proof test because the loading mode (remote tension) and size of the crack relative to the

cross sectional area (very small) more closely model structural characteristics than can laboratory specimen. Wide plate specimens often contains a semi-elliptical surface crack of size as large as that which might occur in service [Denys, 1990]. However, only one analytical result exists for a semi-elliptical surface crack, while the others all address centrally located through cracks. The investigation of the semi-elliptical crack will be discussed first. All of the analyses discussed in this section concern plates with welds containing cracks oriented symmetrically in the middle of the weld and on its centerline. Welds are always perpendicular to the loading direction.

Reed and Petrovski [1990] used the instrumented contour illustrated in Figure 15 to estimate the applied  $J_I$  of semi-elliptic surface flaws in double-V welds made between two 15 mm thick plates of HSLA-80 steel. Their study included three matching ratios ranging from 37% undermatched to 17% overmatched and two crack depth to plate thickness ( $a/t$ ) ratios, 0.2 and 0.4. Figure 16 indicates that , for the smaller crack in the undermatched welds, the rate of increase of applied  $J_I$  with increasing applied strain becomes quite rapid for strains exceeding 1.5 times the yield strain. In contrast, the applied  $J_I$  assumes a constant value for all strains above this level in the overmatched weld. This figure provides dramatic testament to the advantages of weld metal overmatching. However, the advantage breaks down for deeper cracks, as demonstrated by the results for  $a/t = 0.4$  shown in Figure 17. These data indicate that all wide plates reached a very high applied  $J_I$  irrespective of weld metal matching. Thus, while overmatching shields shallow cracks in welds from high applied  $J_I$  values, overmatching has only limited advantage for deep cracks. Bearing in mind that adequate non-destructive inspection and evaluation procedures should keep the crack size in structures small compared to the thickness, these data indicate that overmatching has considerable potential for enhancing structural fracture integrity.

Weidian, et al. [1989] performed a finite element analysis of a 37% overmatched wide plate with a square groove joint containing a middle crack severing 20% of the panel width. These investigators studied the effect of the layer thickness (distance between the welded plates) on the applied  $J_I$ . Figure 18 presents their findings which indicate that widening the grooves of an overmatched weld reduces the applied  $J_I$  because this removes the highly strained lower strength plate material from the crack tip.

Dong and Gordon [1990] performed finite element analyses of wide plates having the same crack / weld geometry as used by Weidian, et al. However, these researchers studied a broader range of conditions, as detailed in Table 3. These results are presented in Figure 19 for  $a/W = 0.05$  and in Figure 20 for  $a/W = 0.20$ . At both crack lengths, the undermatched welds experienced a slightly higher applied  $J_I$  than did the overmatched welds once yielding occurred. Further, the applied  $J_I$  for a panel made entirely of the plate material provided a reasonable approximation of the applied  $J_I$  for all of the weldments studied. Finally, no strong effect of the ratio of the weld layer thickness to crack length ( $2h/2a$ ) existed for the range of conditions investigated. These latter two conclusions will be discussed in view of the work of Zhang, et al. [1989] in the following paragraph.

Zhang, et al. [1989] performed a comprehensive finite element study of the effects of strength mismatch and strain hardening mismatch on applied  $J_I$ . They investigated wide plates with square groove butt welds containing cracks 40% of the panel width; Table 4 summarizes the conditions studied. These investigators introduced the concept of an *equivalent yield stress*,  $\sigma_{e0}$ , and an *equivalent strain hardening exponent*,  $n_{e0}$ . The values  $\sigma_{e0}$  and  $n_{e0}$  are defined as those that produce the same applied  $J_I$  in a monolithic wide plate having the equivalent constitutive properties as in a welded wide plate of interest. Figure 21 shows the variation of  $\sigma_{e0}$  with the ratio of weld layer thickness to crack length ( $2h/2a$ ) for both over and under matched (on strength) welded wide plates. These data indicate that if the weld layer thickness ( $2h$ ) exceeds 1.5 times the crack length ( $2a$ ) the equivalent yield strength nearly equals the weld metal yield strength. As the ratio of  $2h/2a$  approaches zero (as the weld disappears), the equivalent yield strength approaches the base metal yield strength. These findings agree qualitatively with the results of Dong and Gordon, who reported close agreement (within  $\pm 12\%$ ) between the  $J_I$  from weldments with  $2h/2a < 0.3$  and the  $J_I$  for a monolithic wide plate having base metal properties.

Figure 22 presents the variation of effective strain hardening exponent with  $2h/2a$  reported by Zhang et al. These data again suggest that, especially for undermatched welds, when the weld layer thickness exceeds 1.5 times the crack length the equivalent hardening exponent will nearly equal that of the weld metal. At the other extreme, as the weld disappears and  $2h/2a$  approaches zero, the equivalent hardening exponent approaches the base metal

hardening exponent. For a wide variety of ferritic-pearlitic and martensitic steels, Barsom and Rolfe [1987] indicate that the strain hardening rate typically increases with reducing yield strength (in ksi) according to Equation (1). Thus, some of the strain hardening matching ra-

$$n = \left[ \frac{\sigma_{ys}}{15} \right]^{\frac{4}{3}} \quad (1)$$

tios in Figure 22 do not occur in practice. This equation indicates that under strength welds are most likely overmatched for strain hardening while over strength welds are undermatched for strain hardening. This allows condensation of Figure 22 into one graph (Figure 23) for common ferritic-pearlitic and martensitic steels. This graph better supports the conclusion that the equivalent strain hardening exponent for a welded joint equals that of the weld metal when the weld layer thickness exceeds 1.5 times the crack length.

While Zhang's concept of an equivalent yield stress and strain hardening exponent for a welded joint appears to work well, certain limitations do exist. For example, the work of Read and Petrovski and of Cray, et al. demonstrated that, for small cracks in welded panels, certain situations can arise where the applied  $J_I$  does not increase with increasing applied displacement because strains begin to accumulate at the fusion boundary. Under such conditions, the equivalent yield stress / strain hardening exponent concept cannot work because the applied  $J_I$  in a monolithic panel will not plateau for the same reason<sup>5</sup>. Therefore, application of Zhang's equivalent yield stress / strain hardening concept should be restricted to situations where  $J_I$  cannot plateau or has yet to plateau. This limits applicability of the concept to cracks of adequate depth to prevent plateauing and to shallow cracks at loads not much above the limit load.

#### Wide Plate Specimens, Summary

The major findings of the investigations discussed above regarding the effect of a weld on the applied  $J_I$  developed in a wide plate specimen are as follows:

- Overmatching the strength of a welded joint significantly reduces the applied  $J_I$  that develops at a fixed remote loading relative to an undermatched condition. Sufficient overmatching will result in strain accumulation in the plate at the fusion boundary. This causes the applied
5. Read [1988] observed, and Dodds and Read [1989] explained, that the applied  $J_I$  for a small crack in a monolithic tensile panel can plateau with increasing strain. In this instance, however,  $J_I$  plateaus because of an asymmetric in plane yielding phenomena (similar to Luders straining in un-notched specimens) that occurs between net and gross section yield. This is not the same mechanism observed in welded cracked panels, where the applied  $J_I$  plateaus due to strain accumulation at the fusion boundary of the weld joint.

$J_I$  to plateau once yielding occurs and not increase farther even though applied displacement continues to increase. However, crack size influences this advantage of overmatching. Once the crack is of adequate size relative to the panel, the plateau does not occur and the applied  $J_I$  will increase rapidly with increasing strain after net section yield even in an overmatched weldment.

- If the true variation of applied  $J_I$  with remote displacement for a cracked weldment does not experience a plateau due to strain accumulation at the fusion boundary, Zhang's equivalent yield stress and strain hardening concept should provide a reasonable estimate of the applied  $J_I$  for the weldment. This concept uses a monolithic cracked panel having an effective yield stress and strain hardening exponent to model the weldment. If the weld layer thickness exceeds 1.5 times the crack size, these equivalent values become the same as the weld metal properties. At the other extreme, welds of thickness much smaller than the crack size behave as if made entirely of the plate material. Between these two extremes a rule of mixtures applies.

These results indicate that overmatched weldments generally will need less weld metal toughness to prevent crack initiation than will an undermatched weld. The equivalent yield stress / strain hardening exponent concept of Zhang, et al. appears valid provided  $J_I$  cannot plateau with increasing strain. However, because cracks in structures are typically shallow, the utility of this concept for use in structural fracture safety assessments is likely to be limited.

### **Weld Strength Matching Effects on Fracture Toughness**

No definitive experimental studies concerning the effect of weld metal matching on fracture toughness have yet been conducted<sup>6</sup>. Figures 24 and 25 present the two data sets available, due to Satoh, et al. [1979] and Cunha and Pope [1986], respectively. These investigators did not hold all other variables constant and change only the weld metal flow properties. Satoh, et al. changed the weld metal flow properties by changing the electrode type, while Cunha and Pope varied weld metal strength by changing the electrode type, the heat input, and the post weld heat treatment. Thus, the apparent independence of fracture toughness and mismatch indicated in Figures 24 and 25 may be real or a true dependency may exist that is masked by toughness variations produced by other variables not controlled in these experi-

6. Recent experimental fracture studies of weldments seem entirely focused on measuring HAZ toughness as part of local brittle zone investigations. While arguably an important engineering problem, HAZ fracture toughness testing stands on even less solid ground than does weld metal fracture toughness testing. A total of four papers concerning the applied  $J_I$  for a crack in the heat affected zone have been published to date [Muller and Veith, 1986; Ibid, 1988; Heuser, et al., 1987; Hayashi, et al., 1990]. All four papers concerned cracks in compact tension specimens, while almost without exception experimental investigations of HAZ toughness are conducted using SE(B) specimens.



ments. Such a lack of dependence would be surprising, given the considerable body of evidence for plate materials which indicates that toughness is inversely related to strength for a fixed alloy system.

## Overall Summary

This article presented a summary of research concerning the effect of weld metal strength mismatch on the deformation and fracture behavior of welded butt joints. All analytical and experimental evidence available indicates that plastic strain concentrates into the zone of the lowest material strength in a transversely loaded weldment. Thus, plastic strains in undermatched weldments concentrate in the weld deposit while in overmatched weldments they concentrate in the plate. Data for both remote bending and for remote tension loading indicates that the driving force to fracture ( $J_I$ ) for a crack in an undermatched weldment generally increases at a much faster rate with increasing plastic strain than for a crack in an undermatched weldment. This effect of weld mismatch is most pronounced for cracks that are either shallow with respect to the testpiece thickness (less than approximately 30% through wall) or small with respect to the gross load bearing cross section (less than between 4% and 21% area reduction). The implications of these trends are summarized below:

### *Fracture Toughness Testing (Single Edge Notch Bend) Specimens*

- Shallow Cracks: Accurate  $J_I$  estimates cannot be derived from experimental test records without explicitly accounting for the presence and mismatch of the weldment. No  $J_I$  estimation schemes yet exist for this specimen type.
- Deep Cracks: By treating the weldment as a monolithic sample made entirely of the weld metal, it may be possible to obtain  $J_I$  estimates of reasonable accuracy from experimental data records. Only one set of finite element results supports this position, however it appears that this approximation will hold provided that only the weld deposit deforms plastically during testing.

### *Wide Plate Tension Specimens*

- Shallow (or Small) Cracks: The "shielding" of cracks in welds from high applied  $J_I$  by overmatching is most pronounced in this instance. Overmatched weldments experience a plateau at a certain plastic strain level after which no appreciable increase of applied  $J_I$  occurs. Undermatched weldments exhibit no such plateau. These data indicate that, if sufficient non-destructive controls can ensure that cracks in structures remain small, then overmatched weld deposits require considerably less toughness to prevent failure than do undermatched weldments. In fact, specifying a fracture toughness somewhat higher than the  $J_I$  plateau for the largest crack likely to exist in a structure would be a rational first approximation of a toughness

criteria based on performance requirements. However, no simple  $J_I$  estimation schemes yet exist for this specimen type.

- **Deep (or Large) Cracks:** The rate of  $J_I$  increase with increasing plastic strain is still less rapid for cracks in overmatched welds than for cracks in undermatched welds, however no  $J_I$  plateau occurs for overmatched weldments in this instance. The applied  $J_I$  can be estimated with formulas for a monolithic plate of the same geometry made of a material having the *equivalent* yield stress and strain hardening exponent proposed by Zhang, et al. These equivalent properties become those of the plate material when the weld layer thickness becomes small compared to the crack length (weld layer thickness / crack length approaching zero). At the other extreme, the equivalent properties become those of the weld metal when the weld layer thickness becomes large compared to the crack length (weld layer thickness / crack length above 1.5).

Some evidence suggests that weld groove geometry influences  $J_I$  values but does not drastically alter the trends noted above.

Only very limited experimental evidence exists concerning the effects of weld strength mismatch on weld metal toughness. Available data indicates no significant toughness variation with strength matching ratio. If correct, this indicates that undermatching can only reduce the factor of safety against fracture for any particular structure. However, such a lack of dependence would be surprising, given the considerable body of evidence for plate materials which indicates that toughness is inversely related to strength for a fixed alloy system.

**Table 1: Effect of Weld Joint Geometry on Strain Localization in Elliptical Explosion Bulge Tests of Overmatched Welds.**

Weld Joint Geometry	Strength Matching Ratio <sup>1</sup>	Global Radial Strain	Local Strain at Weld Centerline	Local Strain / Global Strain [%]
Square Groove Gap = Plate Thickness	58% Overmatch	0.066	0.016	24%
Double-V 60° Bevel	89% Overmatch	0.091	0.030	33%

Note: 1 – Ratio of uniaxial stresses at an applied strain of 0.05.

**Table 2: Finite Element Results of Bleackley, et al. Illustrating the Effects of Weld Joint Geometry on Applied  $J_I$ .**

Joint Geometry	Joint Description	Gross Section Yielding Design Curve Slope ( $\propto J_I / \Delta_{LL}$ )
Double – V Groove	90° included angle 15.3 mm root gap	35
Single – V Groove	49° included angle 5.1 mm root gap	92
Square Groove	10.2 mm wide groove	114
Homogeneous using Plate Flow Properties	N/A	82
Homogeneous using Weld Flow Properties	N/A	94

Common Features:

1. Cracks located at weld centerline in weld cap
2.  $a/W = 0.1$
3.  $W = 51$  mm
4. Weld models are 15% undermatched
5. Equal strain hardening rate in weld and plate

**Table 3: Wide Plate Conditions Investigated by Dong and Gordon.**

a/W	Matching Conditions			
	Under 25%	Even All Base Metal	Even All Weld Metal	Over 25%
0.05	1/2	X	X	1/2
0.20	1/8 and 3/10	X	X	1/8 and 3/10
Comments: 1. Table entries give ratio of weld layer thickness to crack length (2h/2a). An 'X' indicates that an analysis was performed assuming the entire panel to be made from the material indicated. 2. A Ramberg-Osgood strain hardening exponent of 10 was used for all materials.				

**Table 4: Wide Plate Conditions Investigated by Zhang, et al.**

Variable	Range Investigated
Strength Matching Ratio ( $\sigma_{ys}^{weld} - \sigma_{ys}^{plate}$ ) / $\sigma_{ys}^{plate}$	20% Undermatched to 25% Overmatched
Hardening Matching Ratio <sup>1</sup> ( $n^{plate} - n^{weld}$ ) / $n^{plate}$	66% Overmatched to 100% Undermatched
Weld Layer Thickness / Crack Length Ratio 2h / 2a	0 to 1.5
Notes: 1. n is the Ramberg-Osgood strain hardening exponent, which approaches 1 for linear elasticity and infinity for perfect plasticity. The hardening matching ratio will be negative (undermatched) if the weld hardens less than the plate and positive (overmatched) if the weld hardens more than the plate.	

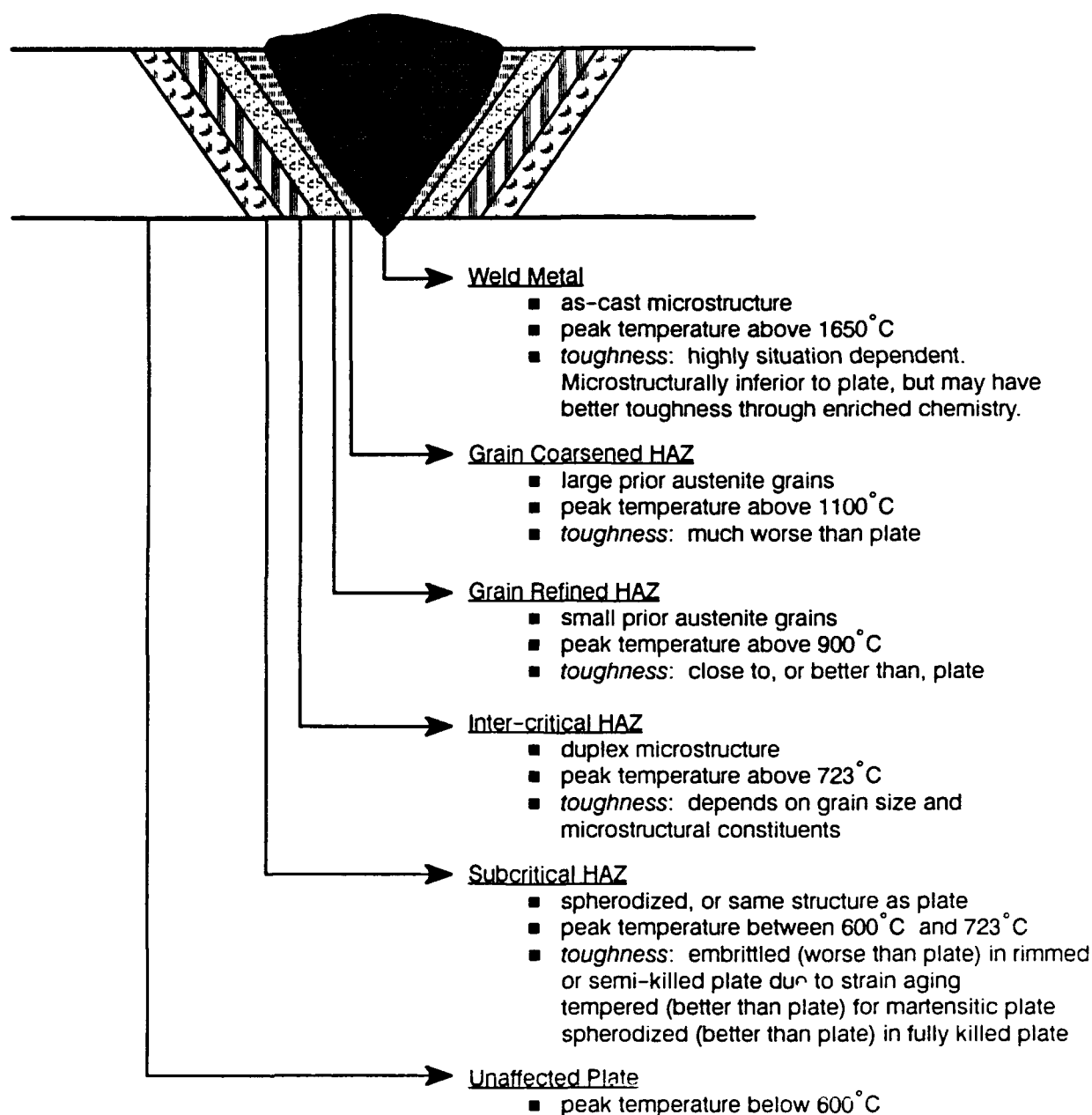


Figure 1: Common microstructural and toughness variations in a single pass steel weldment, condensed from Kerr [1976].

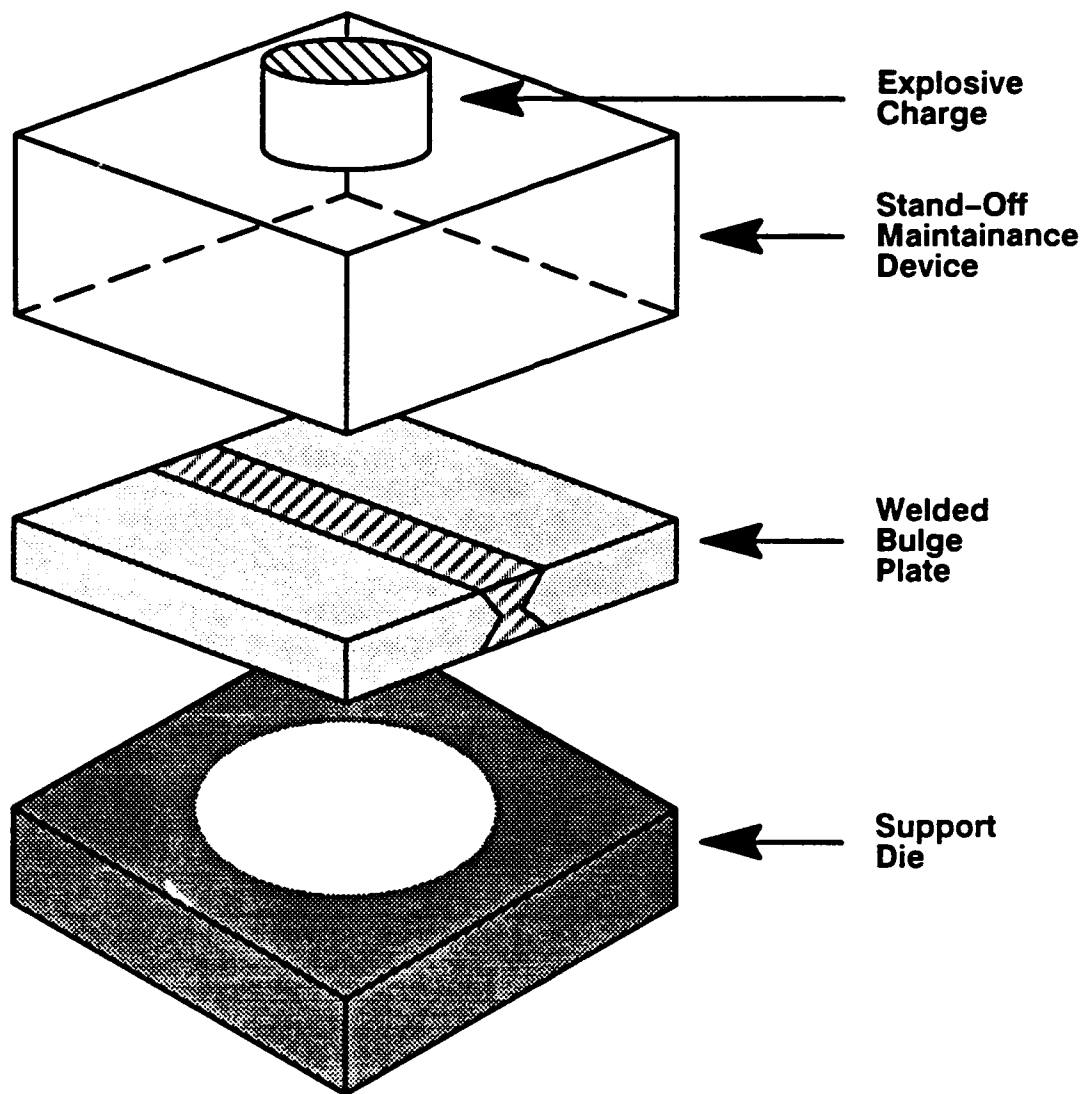


Figure 2: Expanded view of experimental set-up for explosion bulge tests [Hartbower and Pellini, 1951(a) and 1951(b)].

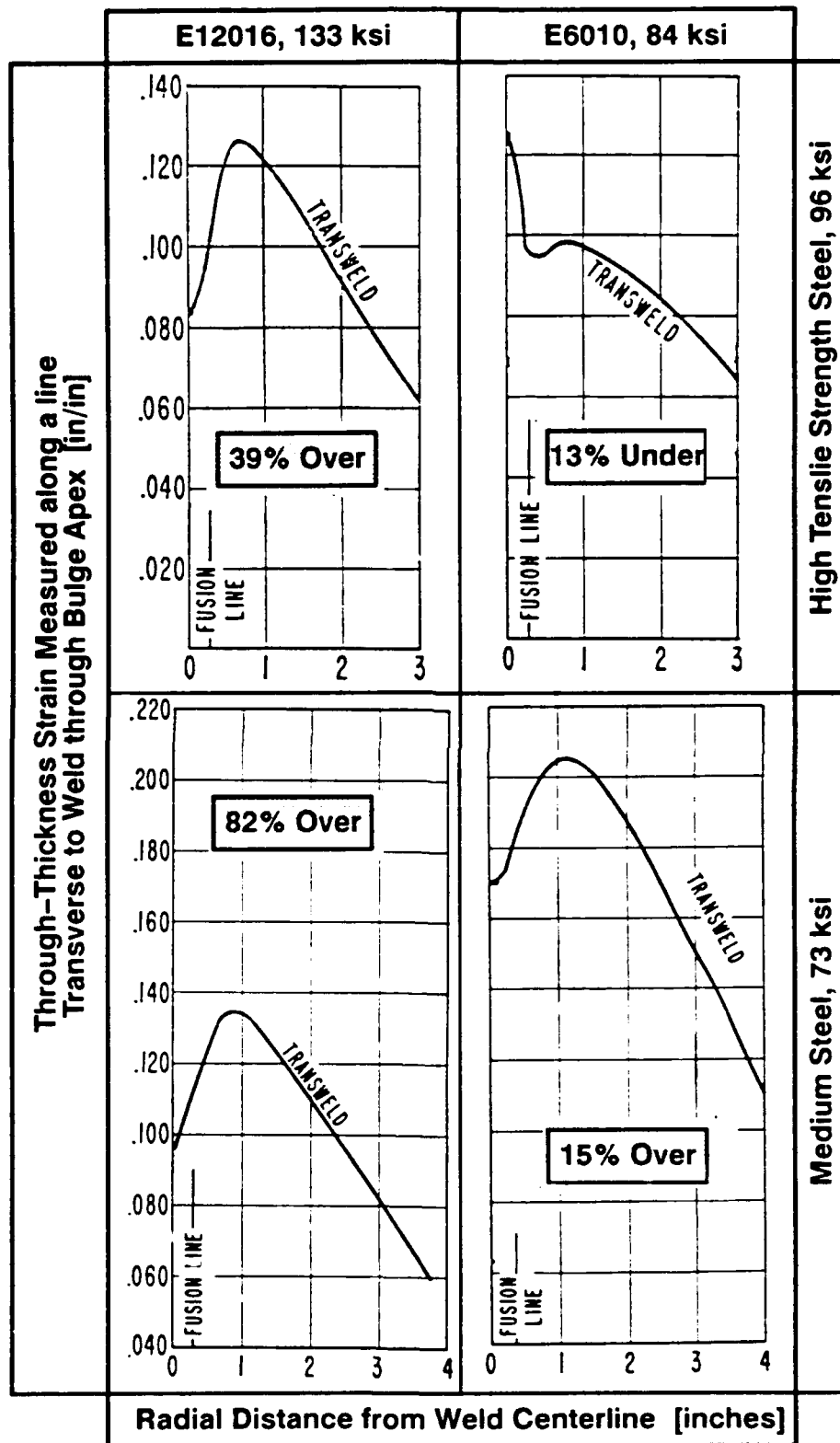


Figure 3: Strain distribution transverse to double-V groove weldments in explosion bulge test panels [Hartbower and Pellini, 1951(a)].

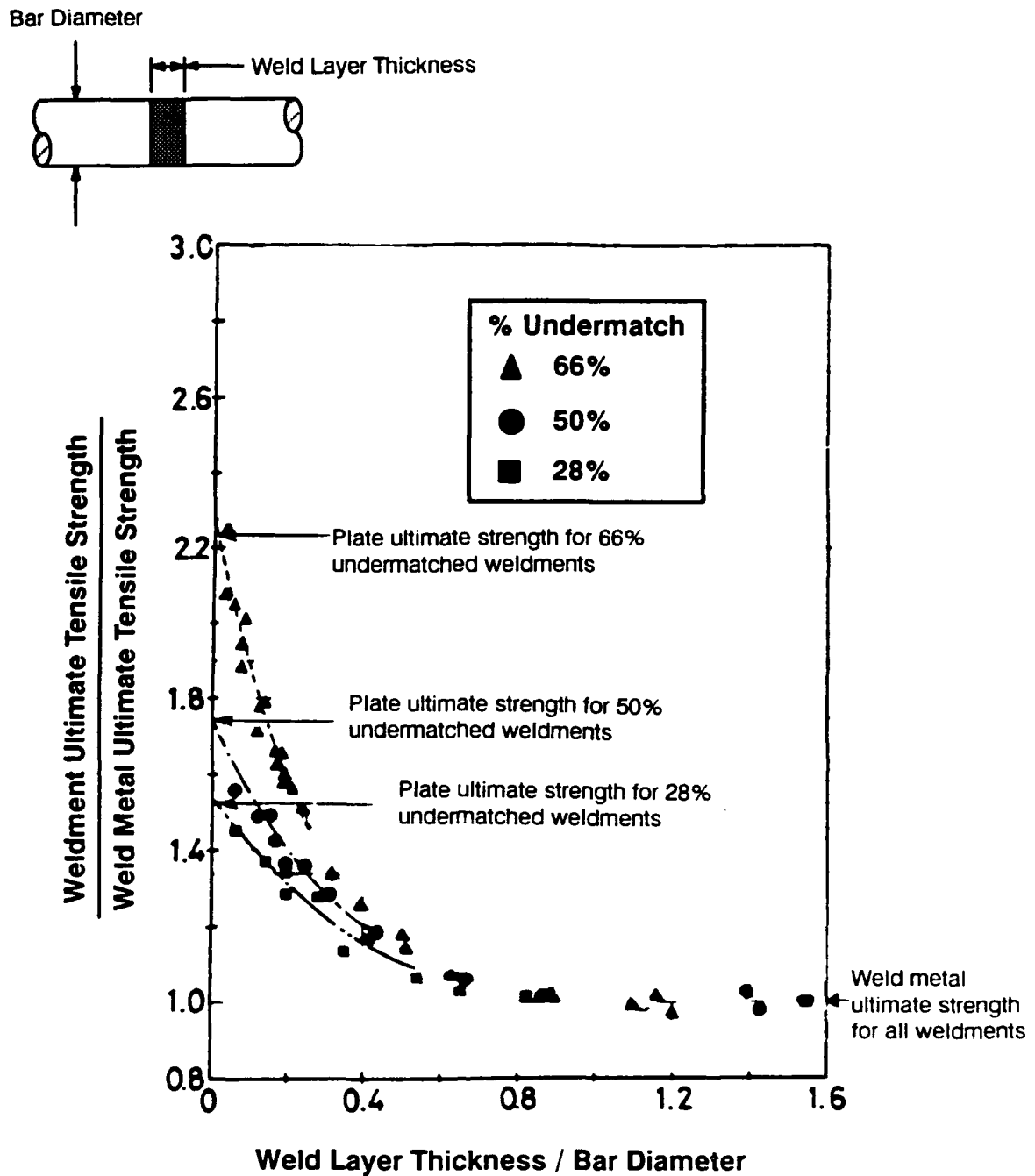


Figure 4: Influence of weld layer thickness (gap between plates joined) on the ultimate tensile strength of the weldment for round bar specimens [Sato and Toyoda, 1970(a)].



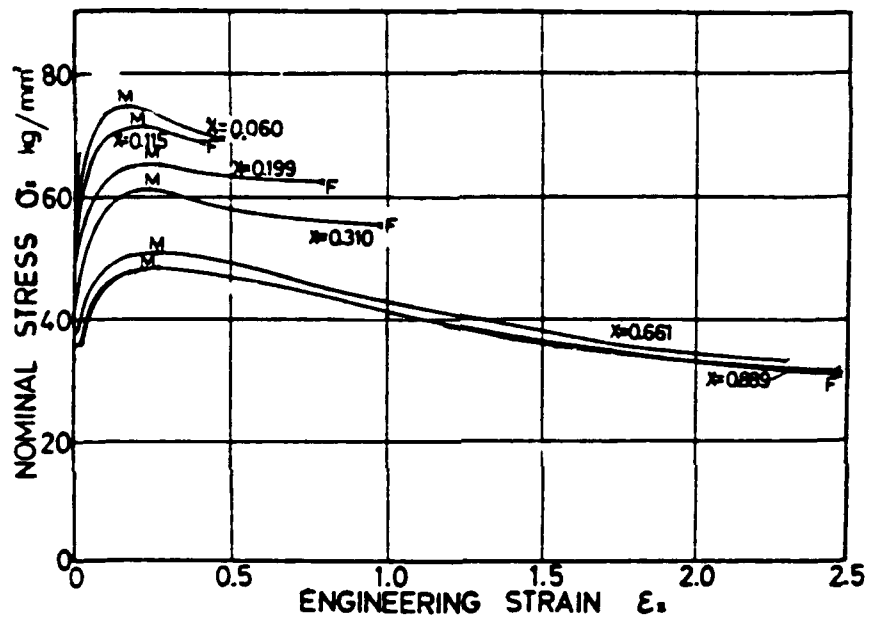


Figure 5: Influence of weld layer thickness (gap between plates joined) / bar diameter (X value) on the failure strain (F) and strain at maximum load (M) for 50% under-matched round bar specimens [Sato and Toyoda, 1970(a)].

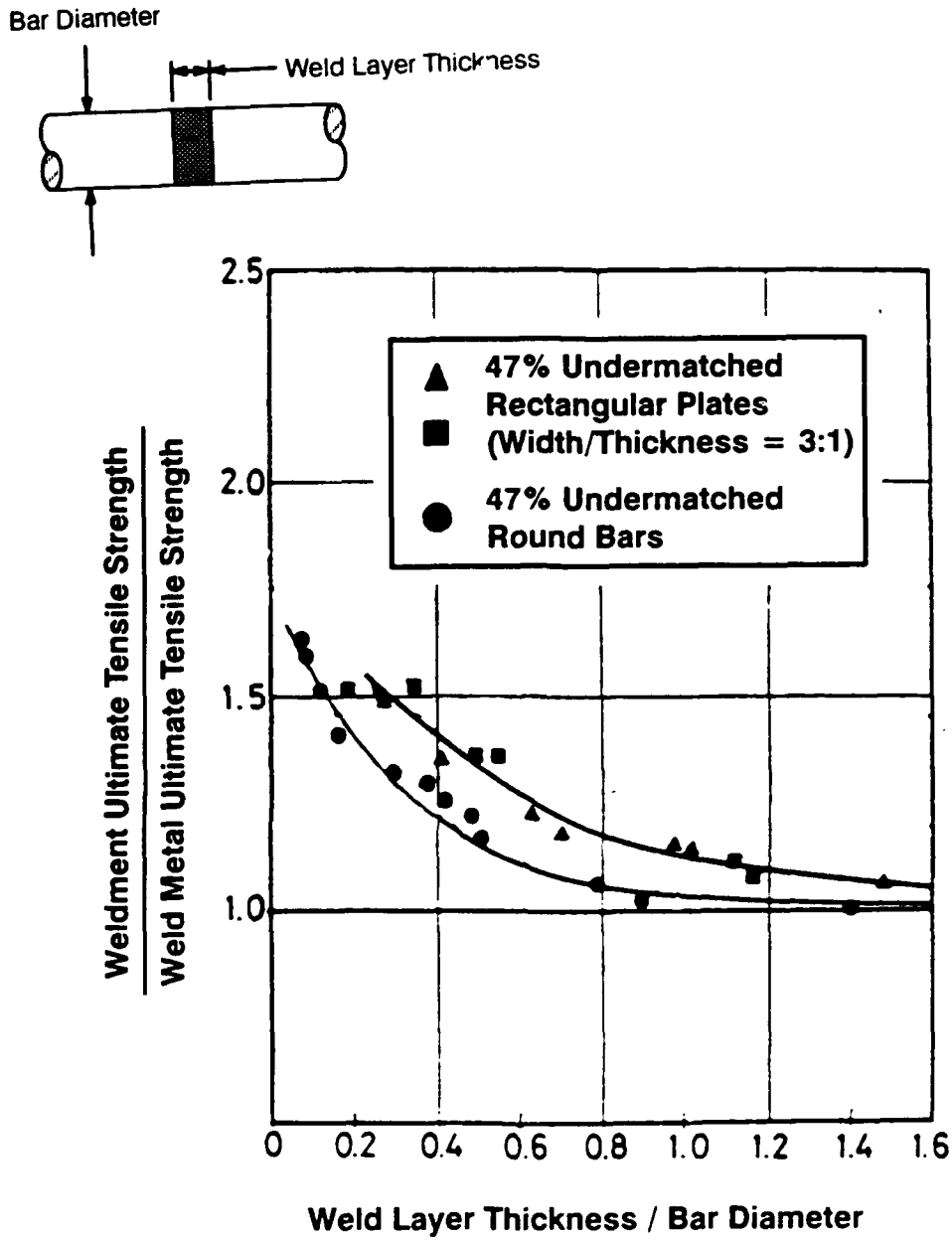


Figure 6: Effect of testpiece aspect ratio on the weldment ultimate tensile strength [Sato and Toyoda, 1970(b)].

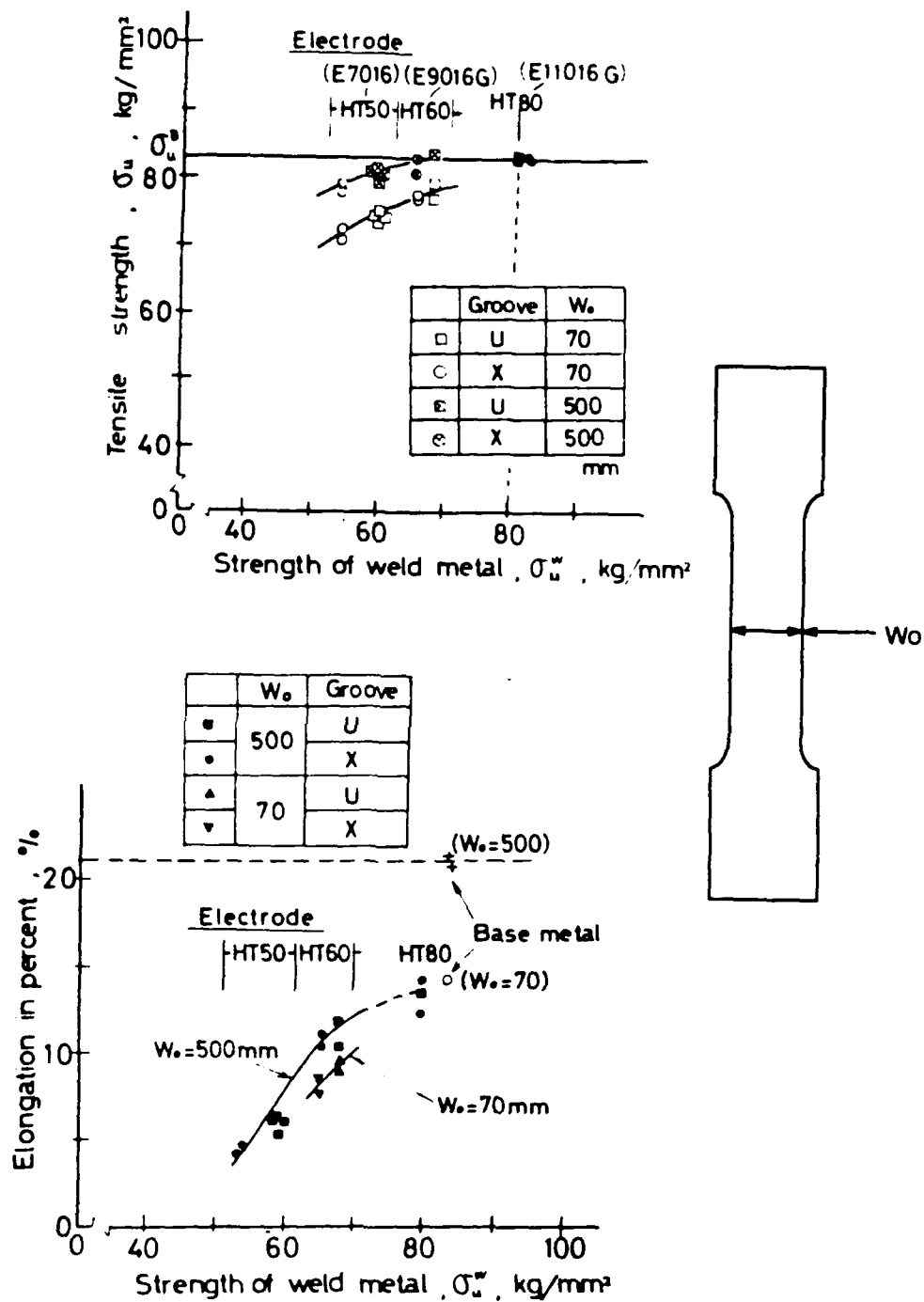


Figure 7: Effect of weld groove geometry and panel width on the ultimate tensile strength and ultimate tensile elongation of 70mm thick HT80 weldments [Sato and Toyoda, 1975].

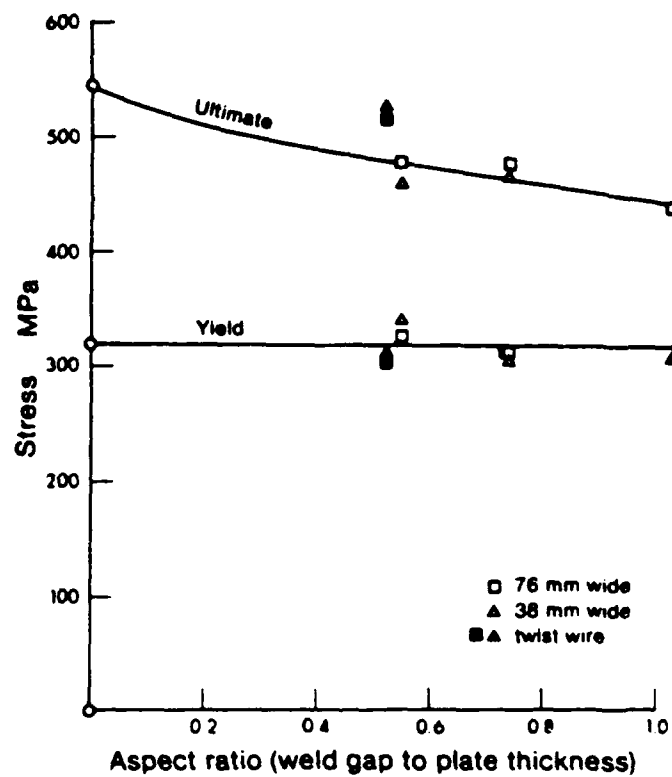


Figure 8: Effect of weld layer thickness on weldment yield and ultimate tensile strength for rectangular cross section tension specimens (width to thickness ratio of 1.5:1) cut from stress relieved ASTM A516 Grade 70 weldments [Patchett and Bellow, 1983].

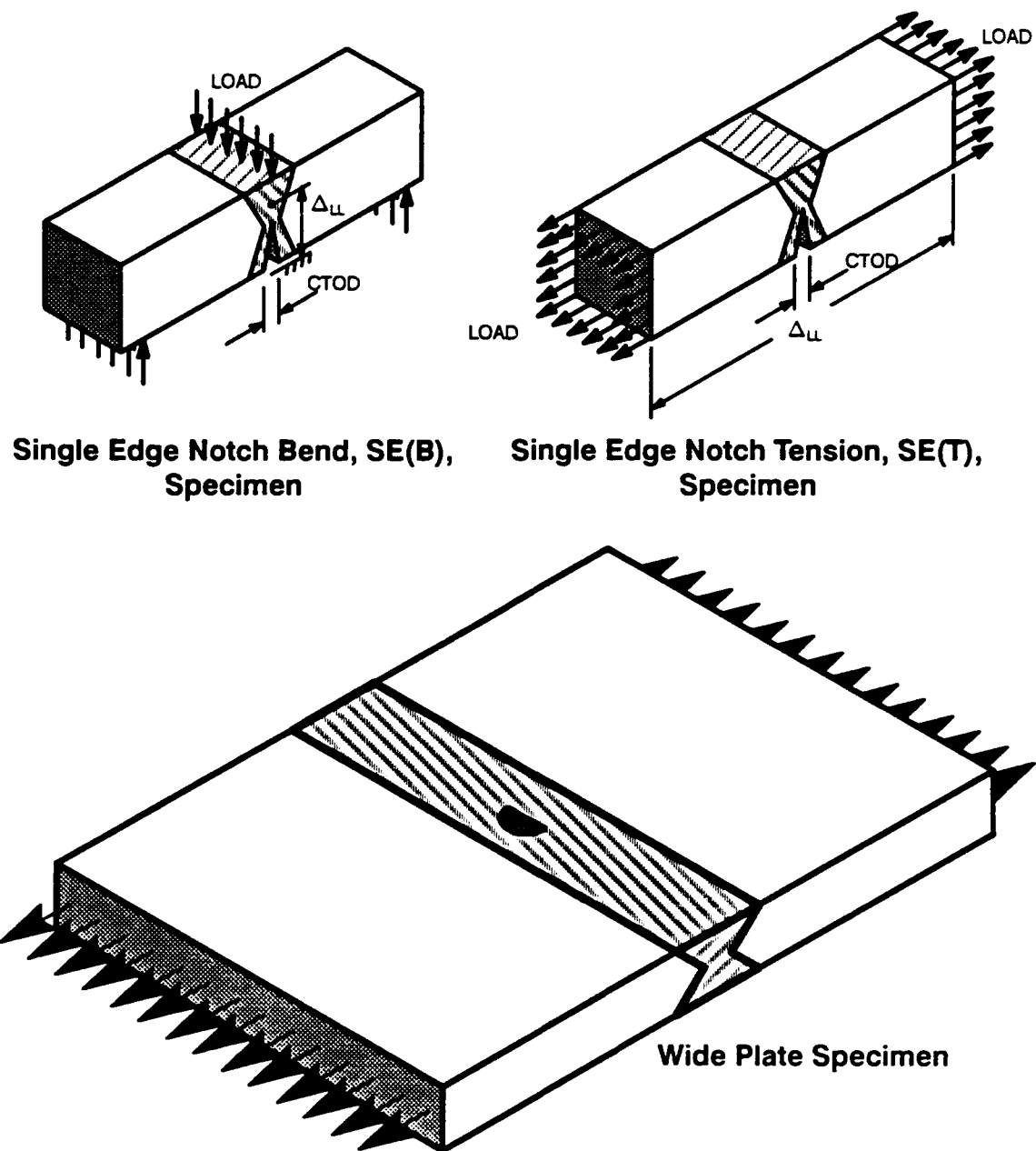


Figure 9: Schematic diagram of testpieces for fracture mechanics tests of weldments.

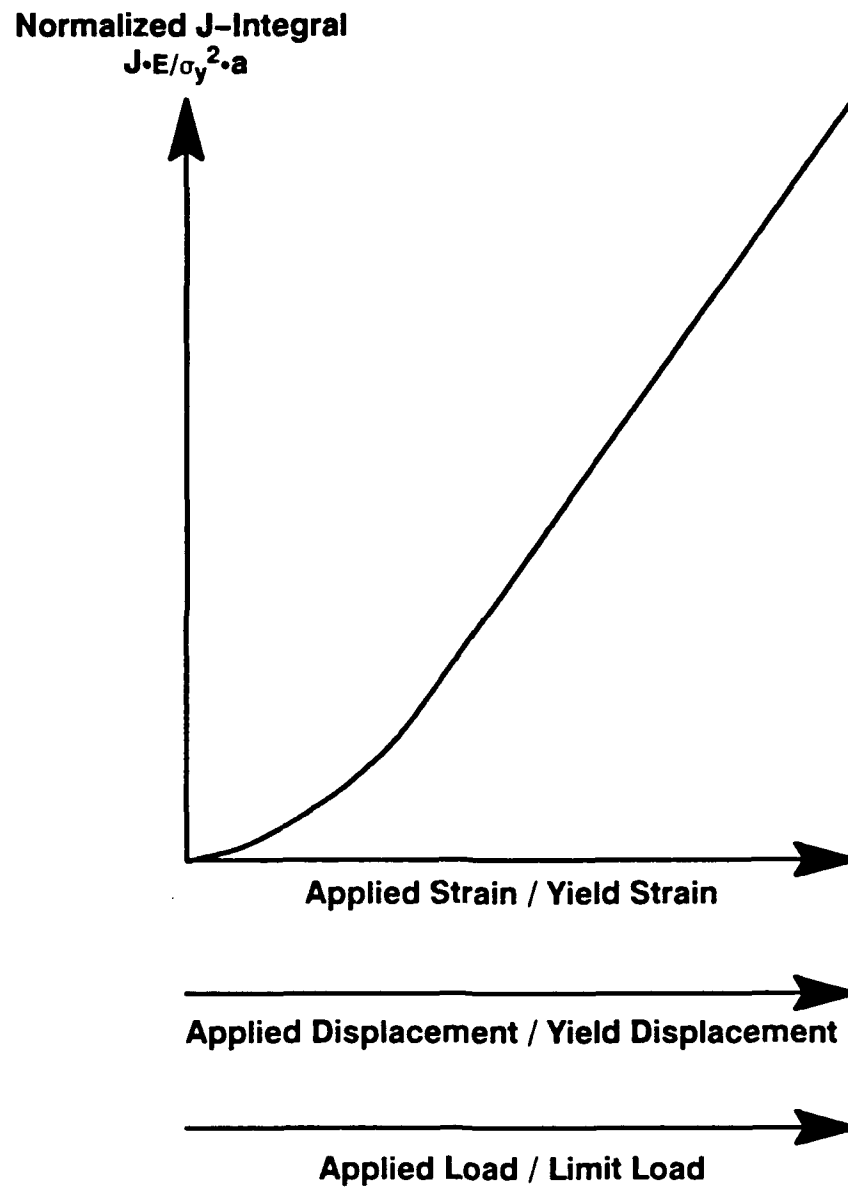


Figure 10: Schematic diagram of Engineering- $J$  design curve format [Turner, 1983].

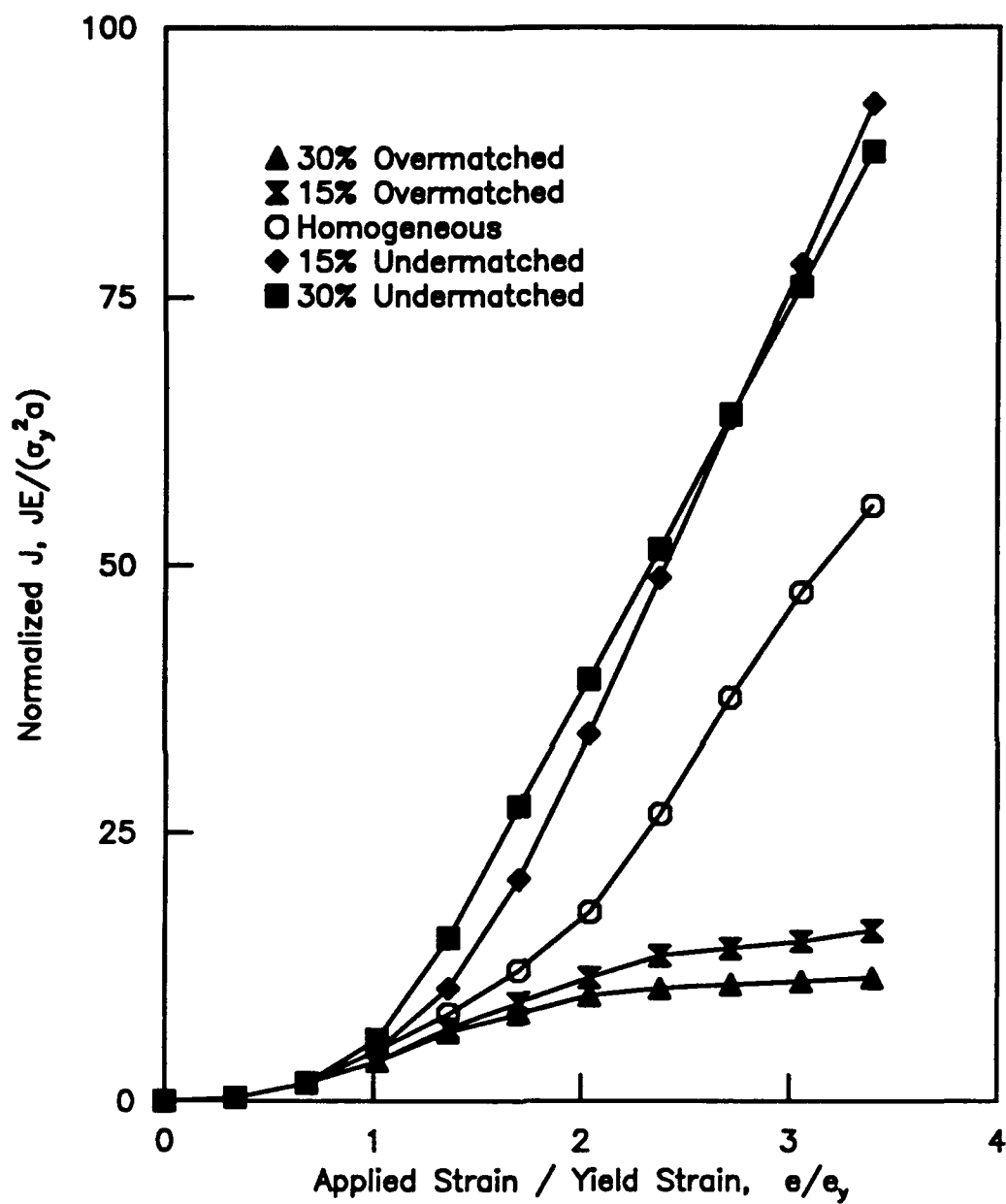


Figure 11: Effect of strength matching ratio on the variation of J with applied strain for 0.1 a/W SE(B) specimens [Cray, et al., 1989].

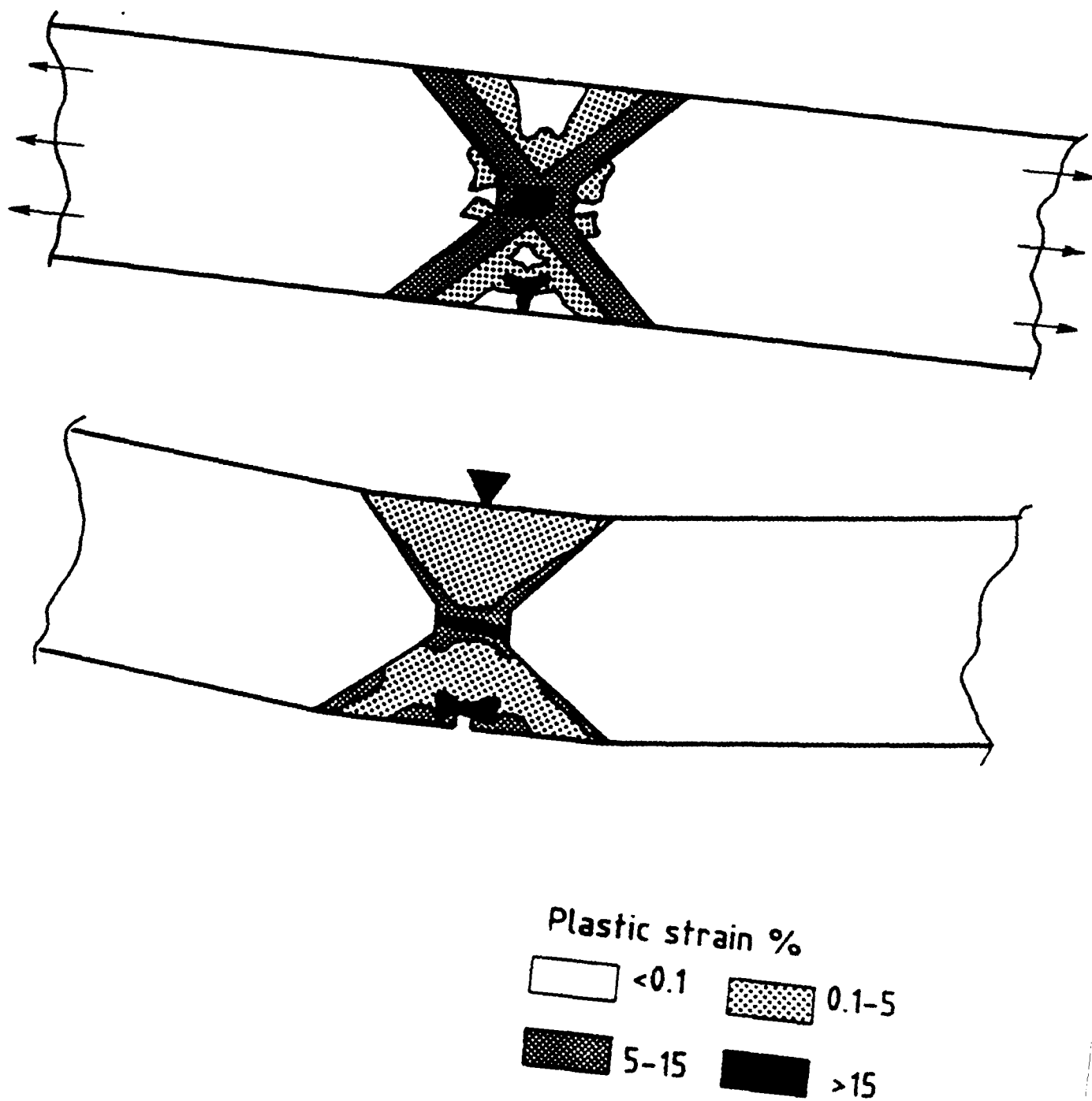


Figure 12: Plastic strain distribution in 30% undermatched double-V butt weldments loaded in remote tension (top) and in remote bending (bottom). Crack depth was .0% of panel thickness. [Cray, et al., 1989]



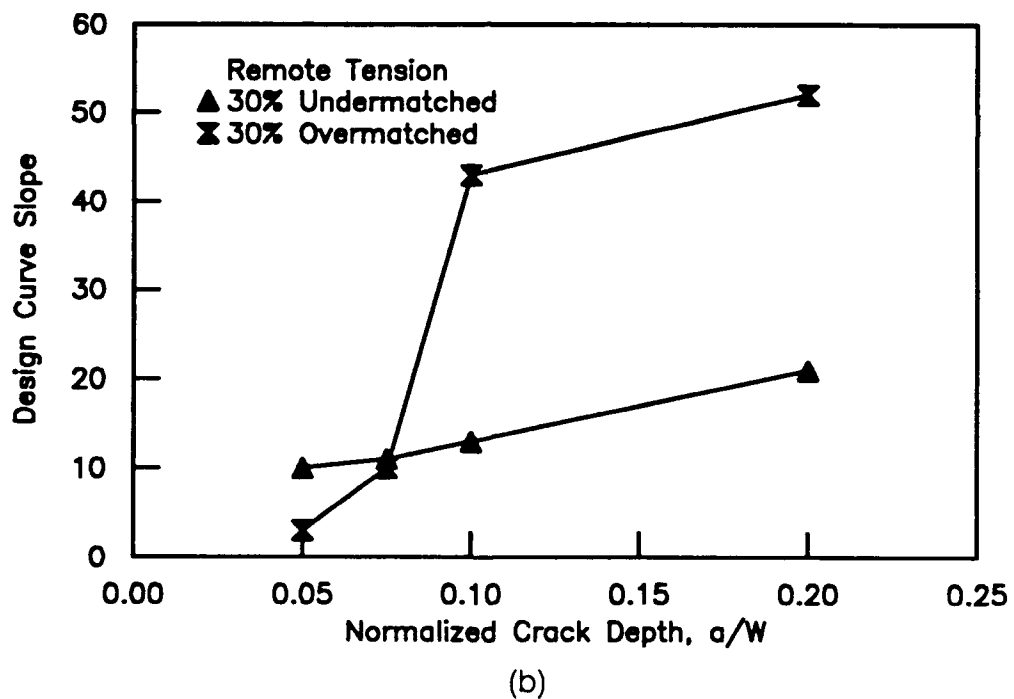
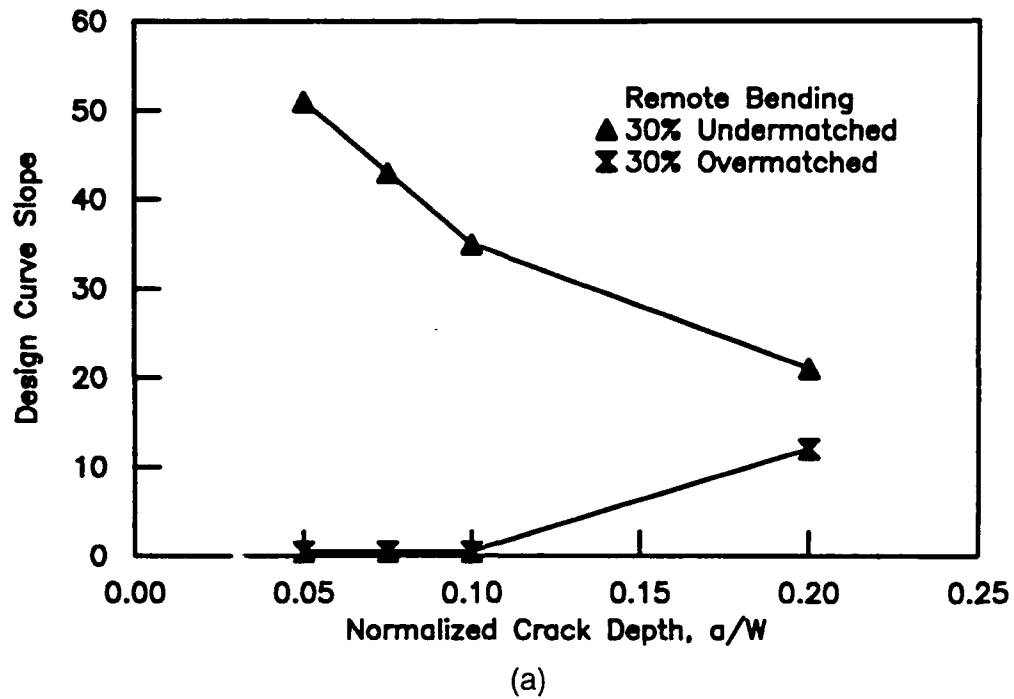


Figure 13: Effect of crack depth, loading mode, and strength matching ratio on the Engineering-J design curve slope of single edge notch specimens once yielding has occurred. (a) SE(B) specimens. (b) SE(T) specimens. [Cray, et al., 1989]

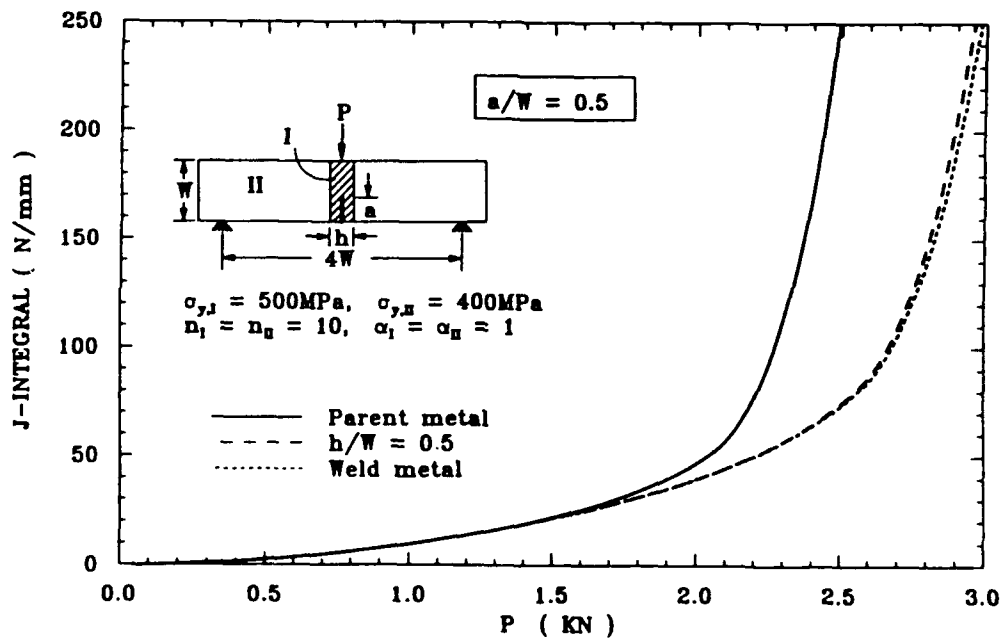
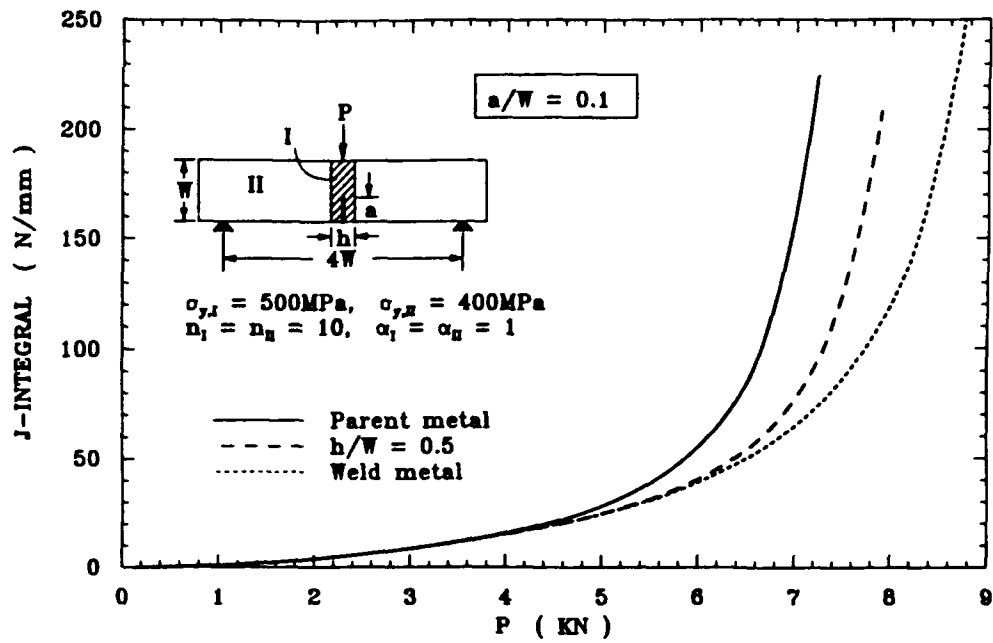


Figure 14: Effect of crack depth on applied  $J_I$  for SE(B) specimens with 25% overmatched butt welds [Dong and Gordon, 1990].



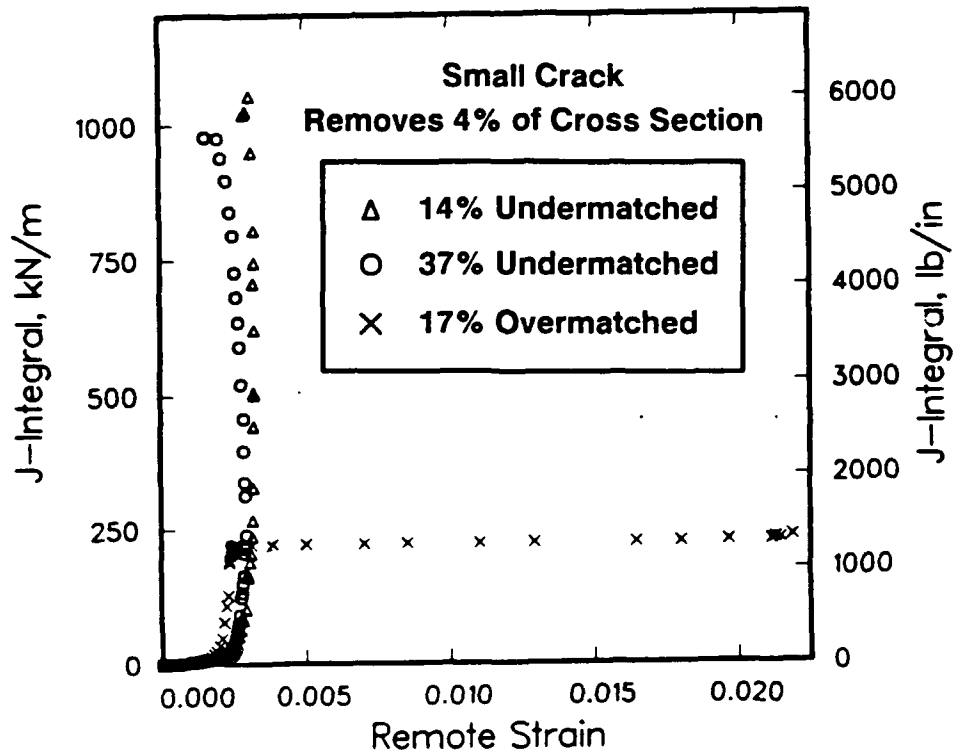


Figure 16: Effect of strength matching ratio on the applied  $J_I$  value developed by a wide plate tension specimen (75 mm x 15 mm cross section) having a surface crack 10 mm long x 3 mm deep on the centerline of a double-V butt weld. Weld and crack were both oriented perpendicular to the loading direction [Read and Petrovski, 1990].

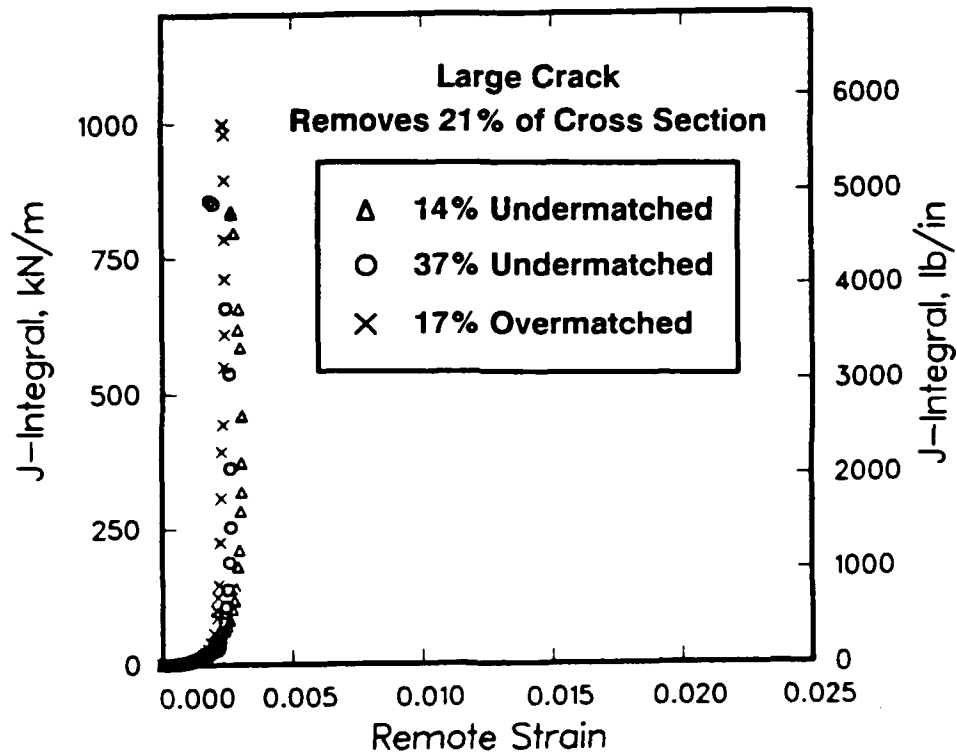


Figure 17: Effect of strength matching ratio on the applied  $J_I$  value developed by a wide plate tension specimen (75 mm x 15 mm cross section) having a surface crack 25 mm long x 6 mm deep on the centerline of a double-V butt weld. Weld and crack were both oriented perpendicular to the loading direction [Read and Petrovski, 1990].

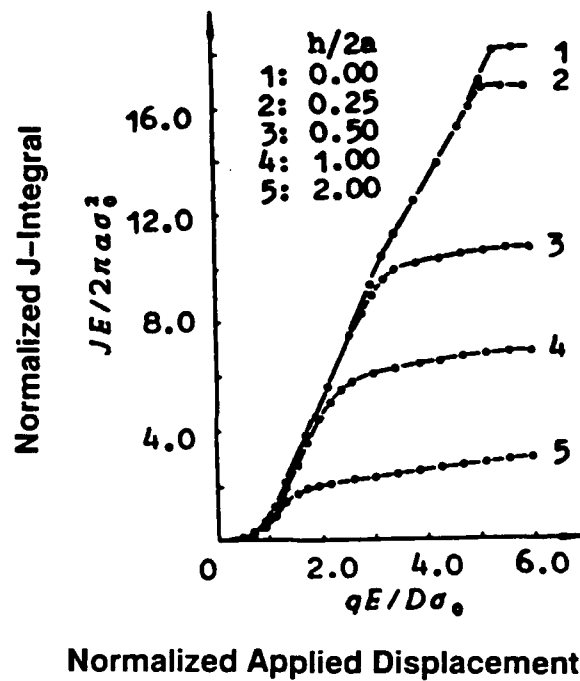


Figure 18: Effect of weld layer thickness ( $h$ ) to crack length ( $2a$ ) ratio on applied  $J_I$  developed in wide plates made from square-groove 37% overmatched butt weldments containing a central through crack cutting 20% of the panel width. Both crack and weld are oriented perpendicular to loading direction [Weidian, et al., 1989].

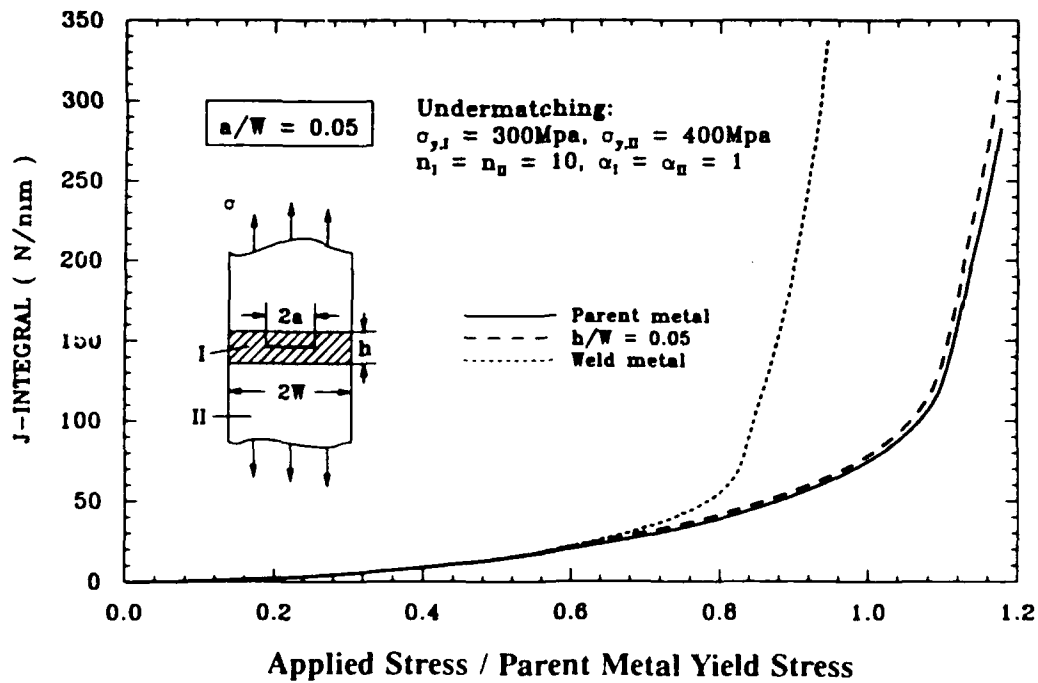
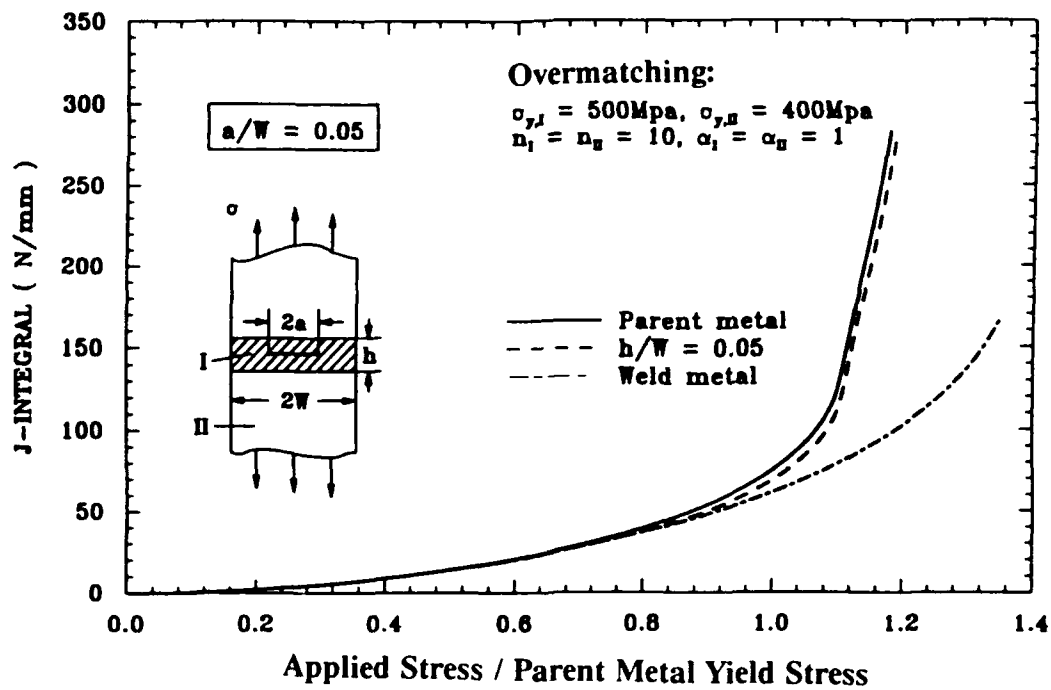
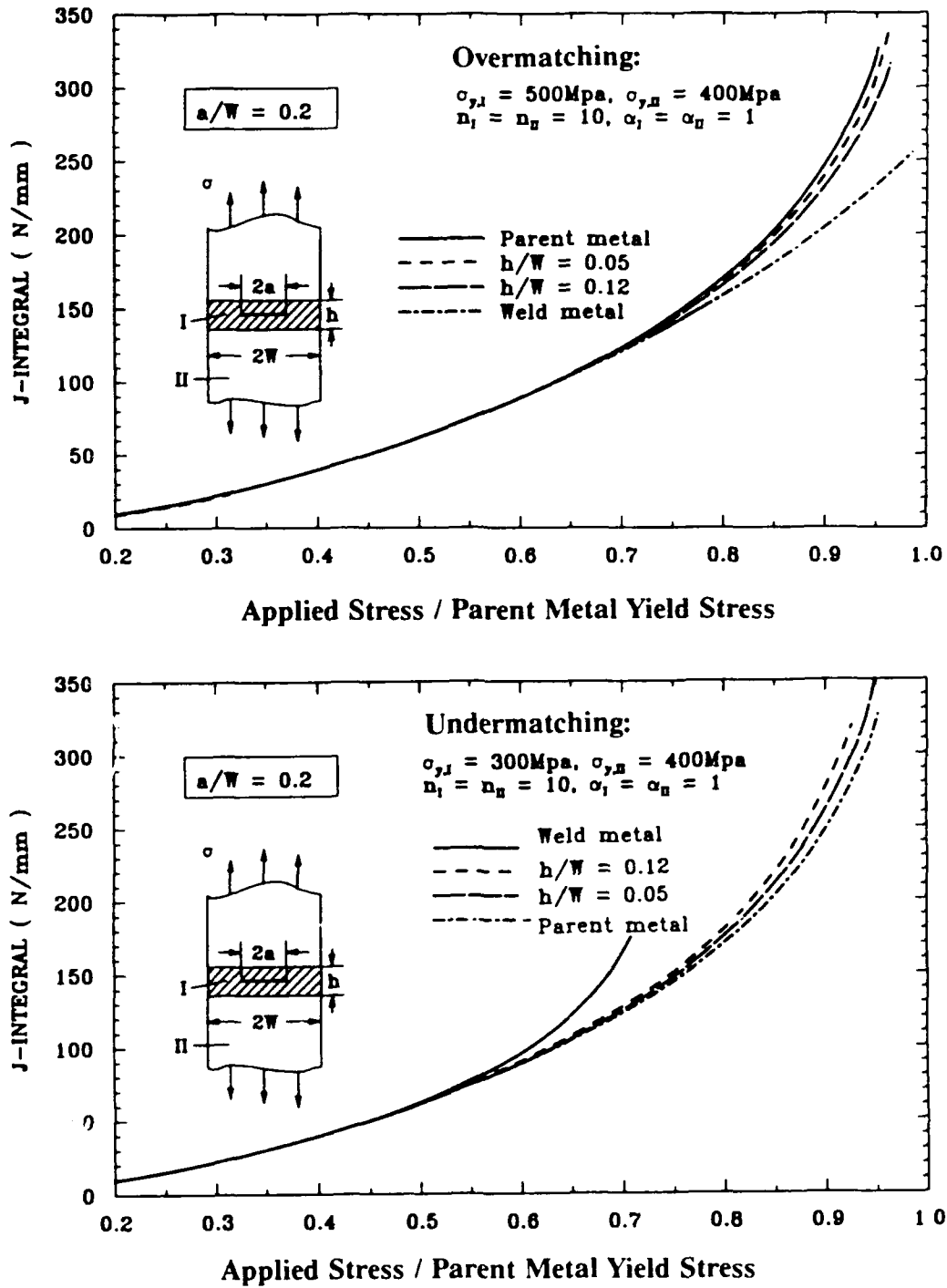


Figure 19: Effect of strength matching ratio on applied  $J_I$  for welded wide plates having through cracks of 5% of the panel width [Dong and Gordon, 1990].





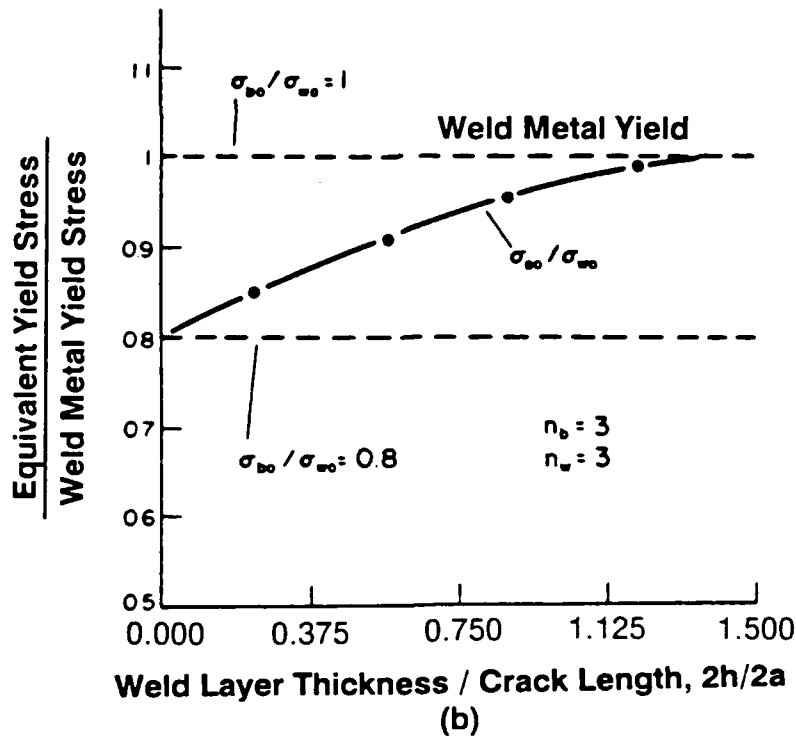
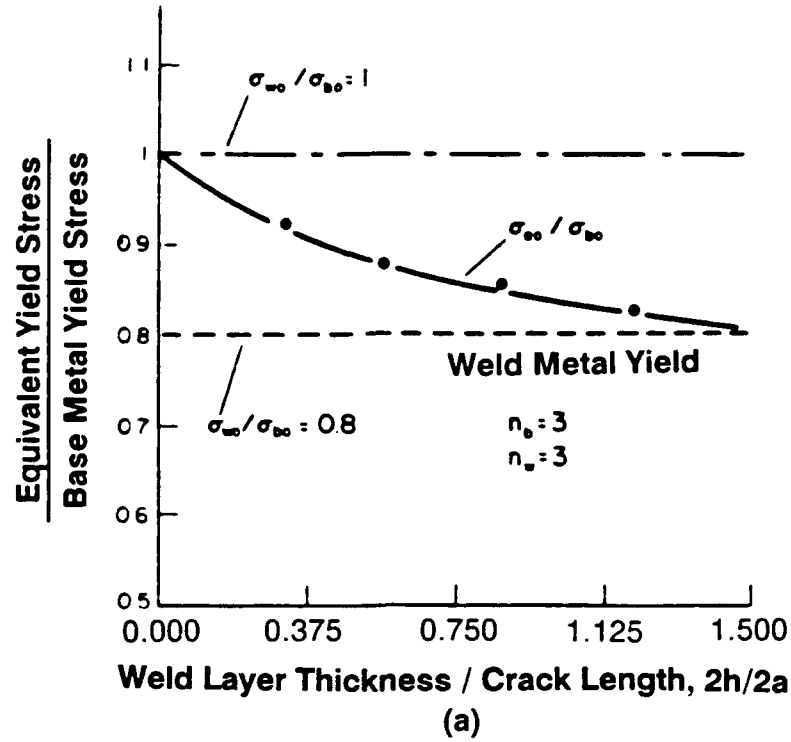


Figure 21: Variation of effective yield stress with the ratio of weld layer thickness to crack length for wide plates made from square-groove butt weldments containing a central through crack cutting 40% of the panel width. Both crack and weld are oriented perpendicular to loading direction. (a) 20% Undermatched. (b) 25% Overmatched. [Zhang, et al., 1990].

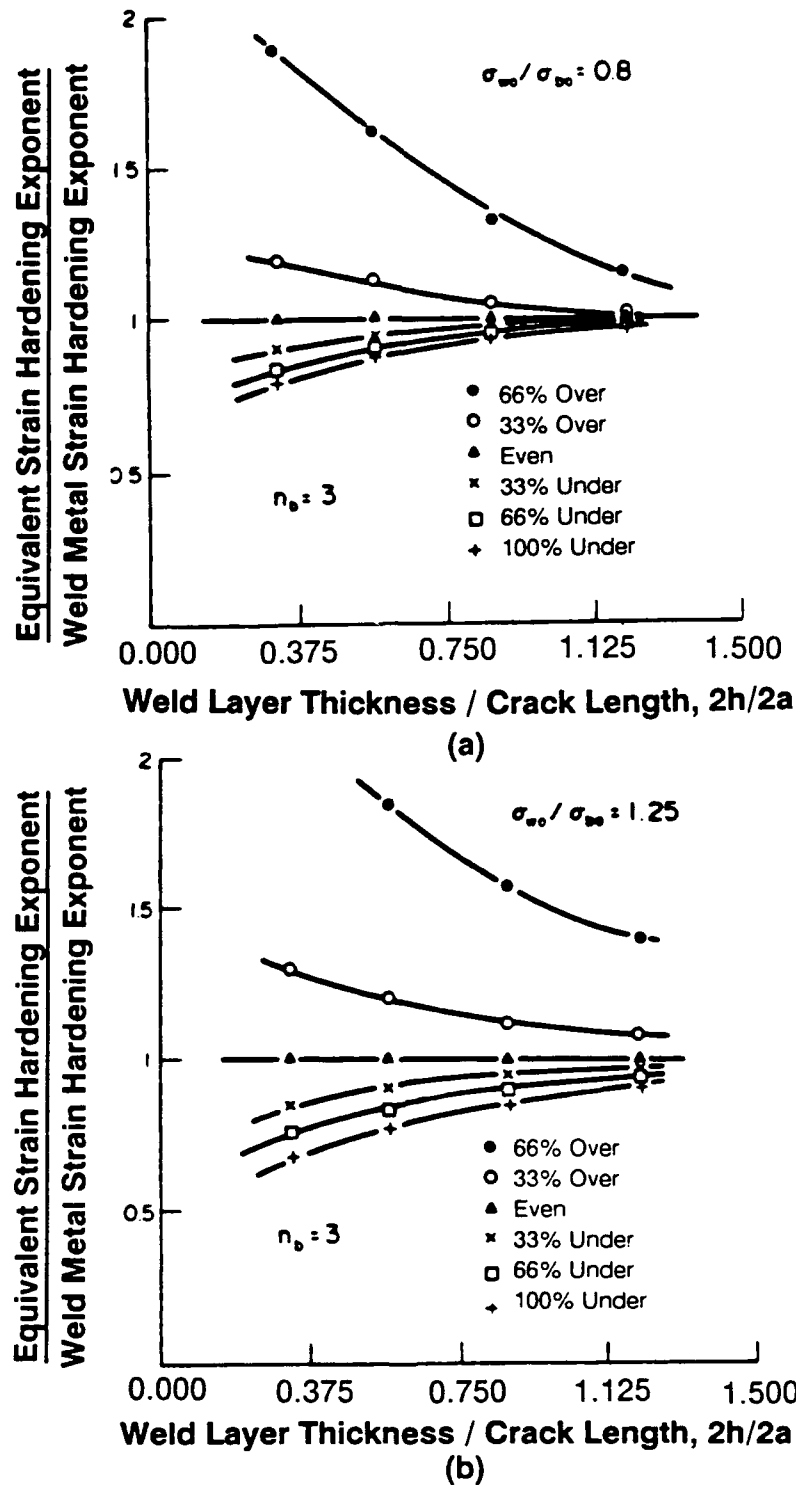


Figure 22: Variation of effective strain hardening exponent with the ratio of weld layer thickness and hardening matching ratio to crack length for wide plates made from square-groove butt weldments containing a central through crack cutting 40% of the panel width. Both crack and weld are oriented perpendicular to loading direction. (a) 20% Undermatched. (b) 25% Overmatched. [Zhang, et al., 1990].

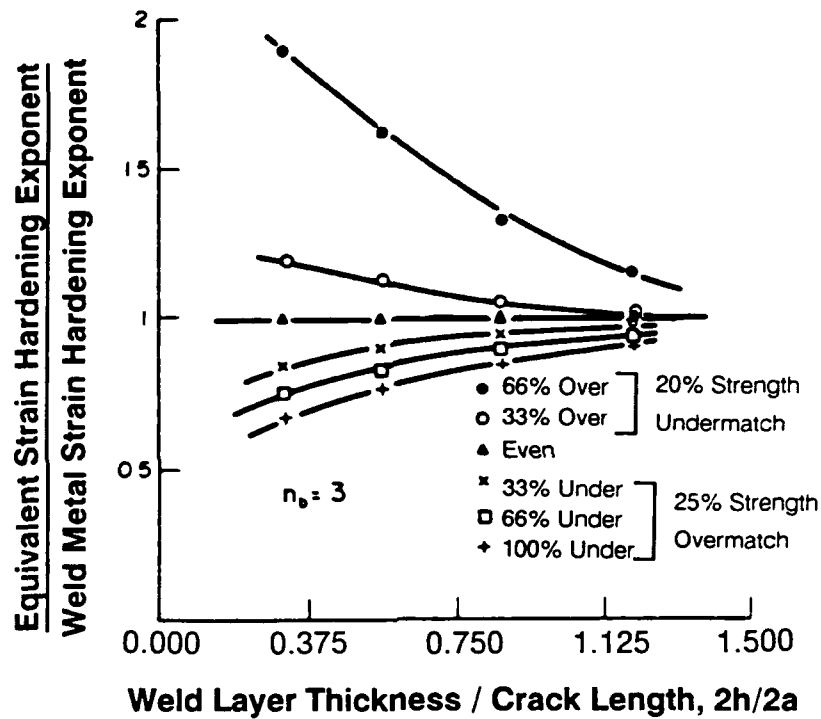


Figure 23: Consolidated plot from the results of Zhang, et al. [1990] showing the variation of effective strain hardening exponent with the ratio of weld layer thickness for common ferritic-pearlitic and martensitic steels. Undermatched welds (on strength) are overmatched for strain hardening, while overmatched welds (on strength) are undermatched for strain hardening.

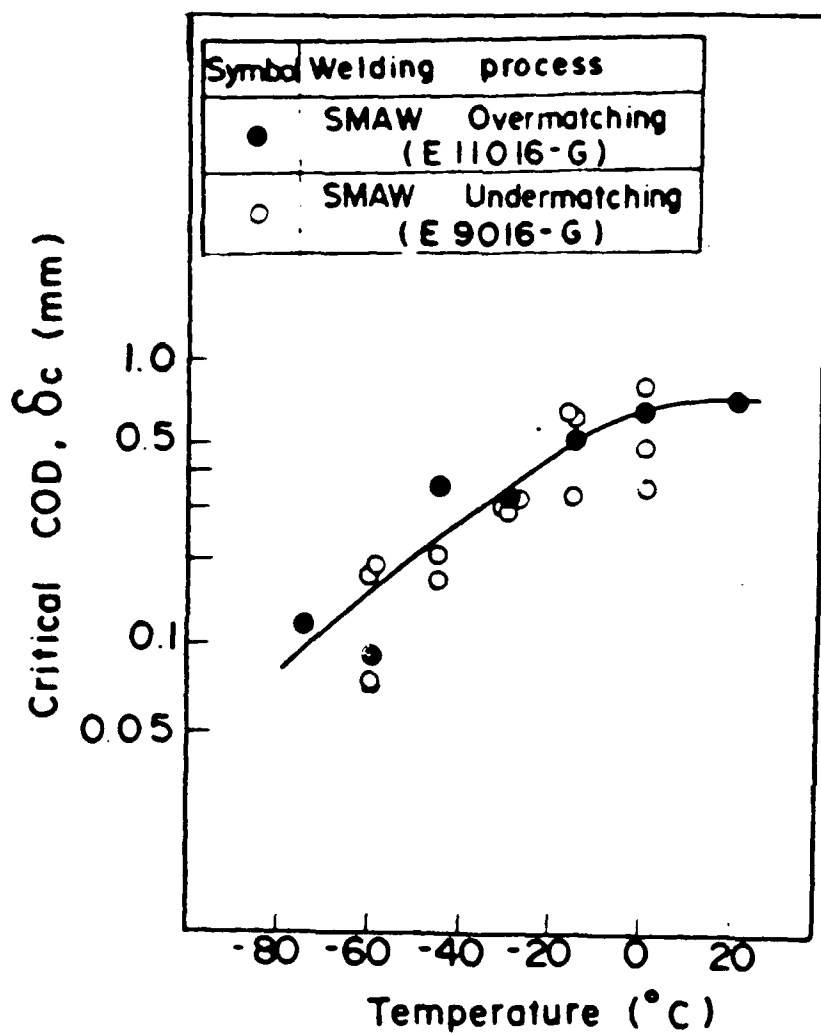


Figure 24: Effect of strength matching (23% undermatched vs. 1% over) on critical fracture toughness ( $\delta_c$ ) values determined by testing deeply notched SE(B) specimens cut from 50 mm thick HT80 steel weldments [Sato, et al., 1979].

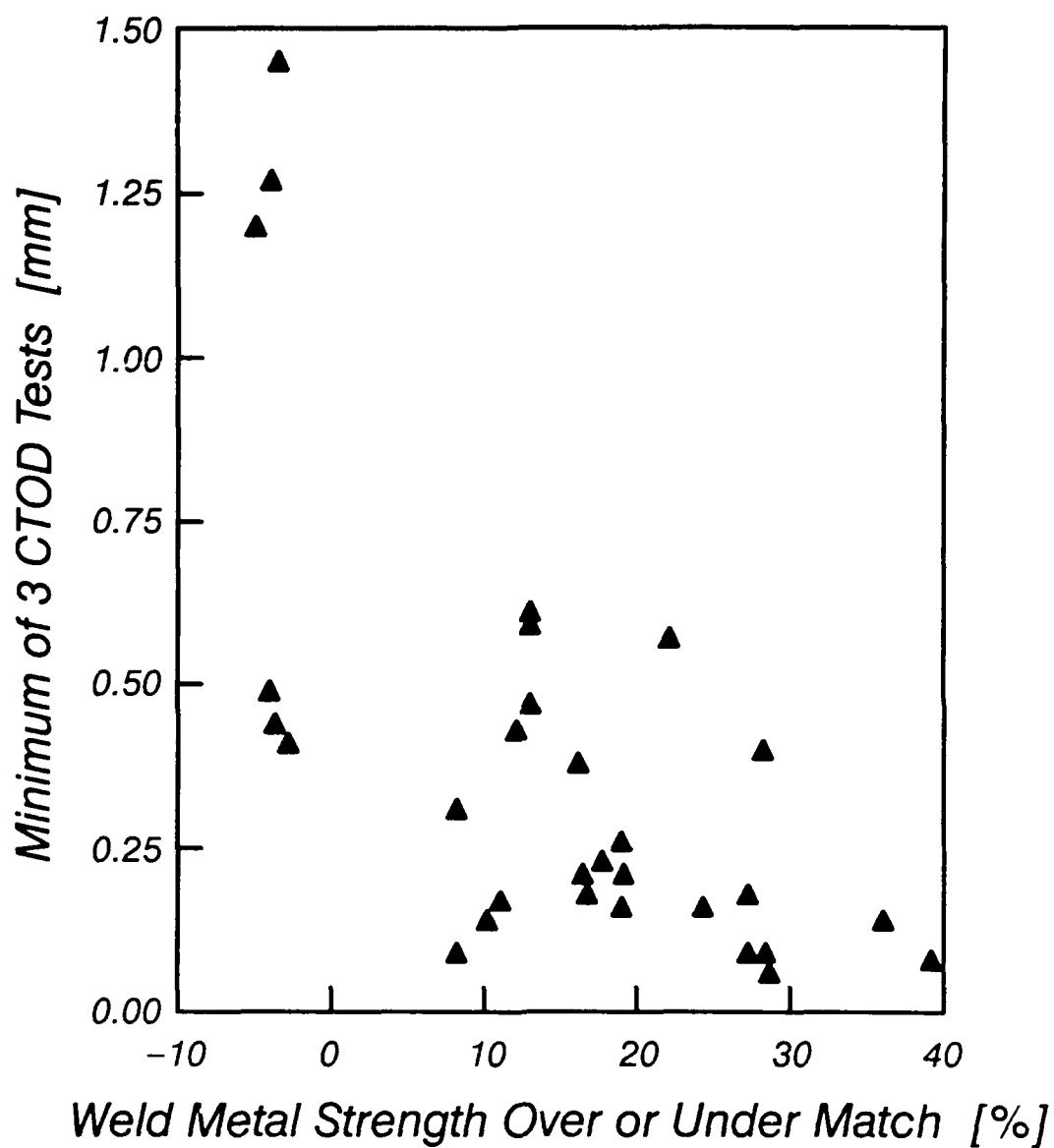


Figure 25: Effect of strength matching ratio on critical fracture toughness (minimum of three  $\delta_c$  values at  $+10^\circ\text{C}$ ) for various self shielded flux core weldments between BS 4360 grade 50D plate [Cunha and Pope].

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